

Extra-Vehicular Activity Welding Experiment

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**Extravehicular Activity Welding Experiment
Final Report**

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FOREWORD

This document constitutes the final report for contract NAS8-37753, Extravehicular Activity Welding Experiment, which is part of the In-Space Technology Experiments Program (INSTEP). The Rocketdyne Division of Rockwell International Corporation was the prime contractor for this effort. The program manager was Dr. G. D. Schnittgrund. The project engineer was Mr. J. K. Watson. Dr. Arthur Nunes was the project manager for NASA Marshall Space Flight Center (MSFC). The California Polytechnic State University (Cal Poly) at San Luis Obispo served as a subcontractor to Rocketdyne. Dr. F. Kolkailah and Dr. D. Walsh were co-principle investigators.

1.0 EXECUTIVE SUMMARY

Welding is a process by which it is possible to create highly reliable, self-sealing structural joints in spacecraft and large space structures with little or no additional weight. It is a versatile process that can be broadly applied to repair situations. A further advantage of welding is that no counter-torque bracing is required as in some mechanical joining methods. For these reasons, welding has been identified by the Pathfinder program as a critical enabling technology for this nation's future space endeavors.

While the development of welding for in-space applications has been slow until now in the United States, it has been pursued aggressively by the Soviet Union for 25 years. The Soviets now have the capability to routinely weld in space and have used the capability for emergency on-orbit repair of their spacecraft.

Of the candidate welding processes, Gas Tungsten-Arc Welding (GTAW) was selected by Rocketdyne as the one offering the most advantages for extravehicular activity (EVA) applications. A detailed comparative evaluation of GTAW, Electron-Beam Welding (EBW), and Laser Beam Welding (LBW) was performed as part of this project. The GTAW was found to offer the greatest combination of benefits from the standpoint of operator and vehicle safety, versatility, crewmember compatibility, and energy efficiency.

The Rocketdyne Division of Rockwell International Corporation has been pursuing the development of in-space welding technology, especially an EVA-compatible variation of the GTAW process, for the last 3 years. The feasibility of the application of this process in a vacuum environment has been demonstrated by Rocketdyne in the laboratory. Recent experimental work conducted by Rocketdyne for NASA on board NASA's KC-135 research aircraft has proven that GTAW is also fully compatible with a low-gravity environment. For several years Rocketdyne has been working with the California Polytechnic State University at San Luis Obispo (Cal Poly) on the development of a GTAW in-place tube welding experiment which will be flown as a Get-Away Special experiment on board the Space Shuttle. This project has produced a welding power supply that has been modified especially for operation in the Shuttle environment. The development of this technology has progressed to the point where it is now appropriate and necessary to proceed with a manned EVA experiment to gather data on operation in the integrated vacuum/low-gravity environment.

Rocketdyne's business is anchored in space. This background provides the basis for successfully undertaking the next step in developing an in-space welding capability. Also important is the expertise provided by the team. The close working relationship already established with Cal Poly will continue to grow. But in addition, discussions have been initiated with the University of California at Berkeley concerning an important role for them in the next phase of this effort. Further, a strong relationship has been established with the Department of Welding Engineering at The Ohio State University. The university will play an active role in the metallurgical characterization of both the baseline and the flight samples generated in the

EVA experiment. Rocketdyne's commitment to this technology was recently demonstrated by participation in a two-week technical visit to the Paton Welding Institute in Kiev, where Soviet in-space welding capabilities have been developed, and the Cosmonaut Training Center near Moscow where the history of Soviet efforts in this field were discussed.

Significant project accomplishments include the performance of experiments on board the KC-135 research aircraft which have demonstrated the feasibility of both manual gas tungsten-arc welding and automated in-place gas tungsten arc tube welding in low-gravity. A preliminary informal review of the project with the National Aeronautics and Space Administration-Johnson Space Center (NASA-JSC) Safety Division indicates that there are no prohibitive safety issues associated with this experiment.

The proposed flight experiment is discussed in extensive detail in the following pages. Preparations for the experiment will be completed within 24 months of contract initiation. An additional 8 months following flight would be required for analysis of the results. The rough-order-of-magnitude (ROM) estimate for this 32-month program is \$2.5 million, which covers approximately 10 man-years of effort, power supply with related packaging hardware, development material, and travel. This estimate is for budgetary and planning purposes only and does not constitute a firm commitment on the part of Rockwell International Corporation. It is anticipated that, in addition, approximately \$450,000 in Government-Furnished Equipment (GFE) will be required. The successful performance of this flight experiment will provide the data necessary to complete the development of a fully functional, highly flexible on-orbit welding capability for repair and assembly.

2.0 INTRODUCTION

Welding provides the means to make highly reliable, leak-free joints in tubes, pressure vessels, and structural members with mechanical properties approaching those of the base metal. Application of welding in the assembly of space structures would provide these capabilities while offering the added advantages of minimizing structure weight, reducing the complexity of assembly interfaces, and increasing system reliability. Furthermore, an operational welding capacity on board a manned space facility would add a new dimension to contingency repair capabilities.

Critical requirements in selecting a welding process for space applications include safety, versatility, reliability, technology availability, and reasonable power requirements. Of the candidate welding processes, GTAW offers the optimum combination of these factors. Gas Tungsten Arc Welding is especially attractive because it can be performed either manually by an individual manipulating the welding torch or automatically by mechanisms designed for specific applications such as the joining of tubes. This process is also extremely versatile because it can be employed both in pressurized and vacuum environments.

The adaptation of this process for use in space was begun several years ago by Rocketdyne, on Corporate funding, with the development of a hollow nonconsumable electrode which enables the stabilization of the arc in vacuum. Rocketdyne is continuing development, characterization, and optimization of the hollow electrode GTAW process and is now beginning to study the human factors associated with welding operations in space. The environmental conditions encountered in extravehicular activity such as the combination of low-gravity, vacuum, and the necessity of pressure suits present significant challenges to welding technology which must be addressed.

The In-Space Technology Experiments Program (INSTEP) provides an opportunity to explore the many critical questions which can only be answered by experimentation in space. The objective of the Extravehicular Activity Welding Experiment definition project was to define the requirements for a spaceflight experiment to evaluate the feasibility of performing manual welding tasks during EVA. Consideration was given to experiment design, work station design, welding hardware design, payload integration requirements, and human factors (including safety).

Through this program, Rocketdyne has defined the requirements for a spaceflight experiment which will provide the basis for development of a fully operational space welding capability. Rocketdyne is prepared to carry this experiment through completion.

This report presents the results of this effort. Included are the specific objectives of the flight test, details of the tasks which will generate the required data, and a description of the equipment which will be needed to support the tasks. Work station requirements are addressed as are human factors, STS integration procedures and, most importantly, safety considerations. The report concludes with a preliminary estimate of the cost and schedule for completion of the experiment through flight and postflight analysis.

3.0 SUMMARY

The significant accomplishments of this project include:

- An experiment has been designed which will provide the data necessary to evaluate the capabilities of astronauts to weld in EVA. This experiment will explore the crewmembers' capabilities and limitations when working in EVA, the interactions of the crewmembers with the welding process, equipment requirements, and the interaction of the welding process with the material being welded in the EVA environment.
- The first-ever attempt by American researchers to perform manual welding in low-gravity was successfully completed.
- The project has been discussed with Lt. Colonel Jerry L. Ross and with Commander Robert "Hoot" Gibson of the NASA-JSC Astronaut Office and their comments have been integrated into the plans for the flight experiment.
- The project plans were reviewed with the NASA-JSC Safety Division. Approaches have been developed for dealing with various safety concerns. No prohibitive safety issues were identified.
- Space Shuttle flight experiment integration requirements were reviewed with the National Space Transportation Systems Office at NASA-JSC.
- Conceptual design of the hardware necessary to support the experiment is complete.
- A detailed simulation of the flight experiment conducted to develop timeline data showed that approximately 4 hours of EVA will be required.
- The ROM estimate for completing the flight experiment project over a 32-month period (including postflight analysis) is estimated for budgetary purposes to be approximately \$2.5 million.
- Tests to develop detailed time study data for EVA tube welding tasks performed by a pressure-suited test subject in a neutral-buoyancy environment are planned.

4.0 BACKGROUND OF WELDING IN SPACE

4.1 TECHNOLOGY NEED

To support the ambitious goals of the United States space program [Ref. 1] a variety of fabrication and manufacturing technologies must be adapted for use in the space environment. Such capabilities will be required for the construction of interplanetary vehicles too large to be boosted intact from the surface of the Earth, for the maintenance and repair of these vehicles during their missions, and for the eventual establishment of bases on planetary surfaces.

It is now recognized that, just as it is crucial to terrestrial manufacturing and construction, welding will play a vital role in the expansion of this nation's presence in the Solar System. Welding has been identified in the In-Space Assembly and Construction portion of the Pathfinder Program as a technology which will be required for future large-scale space missions [Ref. 2]. Primarily, welding is seen as a means of assembling structures for either orbital or interplanetary operations which are too large to be boosted as a whole into space from the Earth's surface. Welding can also serve as a versatile process for repair of a wide variety of structural elements in the event of degradation or damage.

4.2 SPACE PROGRAM APPLICATIONS OF SPACE WELDING

Recent discussion of welding as a possible means of assembling the Space Station Freedom flexible metal-line fluid utility system on orbit raises the potential for near-term application [Ref. 3]. Welding offers increased reliability over mechanical fittings and could provide benefits from the standpoint of reduced mass-to-orbit, lower flight hardware cost, and improved inspectability and repairability. Experience has shown that mechanical couplings for fluid lines on spacecraft do not provide required reliability. One of the lessons learned from the Skylab program was that use of mechanical couplings should be minimized and that welding is a preferred alternative [Ref. 4].

4.3 SOVIET TECHNOLOGY DEVELOPMENTS

Soviet researchers have been actively pursuing the development of the technology for welding in space since the early 1960s [Ref. 5]. In 1969 several competing candidate welding processes were evaluated during an on-orbit experiment using the Vulcan apparatus. Vulcan was a semiautomatic device similar in nature to the Get-Away Special cannisters currently being flown on the Space Shuttle. Of the processes examined, EBW was selected for further development. Soviet efforts progressed to the point of an EVA experiment which was conducted on Salyut 7 in July 1984. In Figure 1 cosmonaut Svetlana Savitskaya is shown performing the experiment. Details of the work station are seen in Figure 2. This experiment utilized a multi-purpose electron-beam device, shown in Figure 3, known as URI. This device is capable of welding, cutting, soldering, and applying metal coatings. Welding efforts were reported as being marginally successful due to difficulties in maintaining the gun-to-work dis-

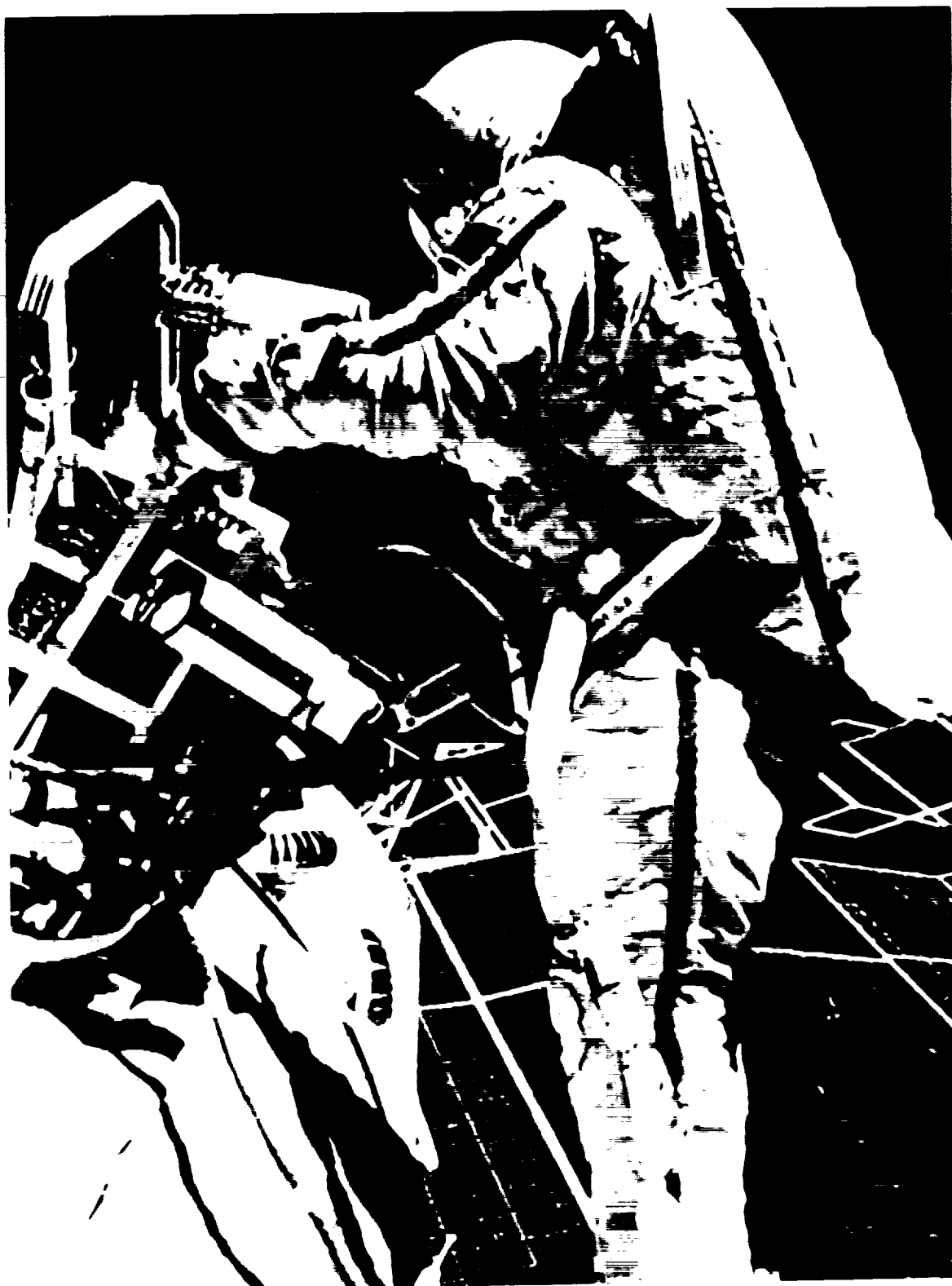


Figure 1. Cosmonaut Svetlana Savitskaya Performing an EVA Welding Experiment in July 1984

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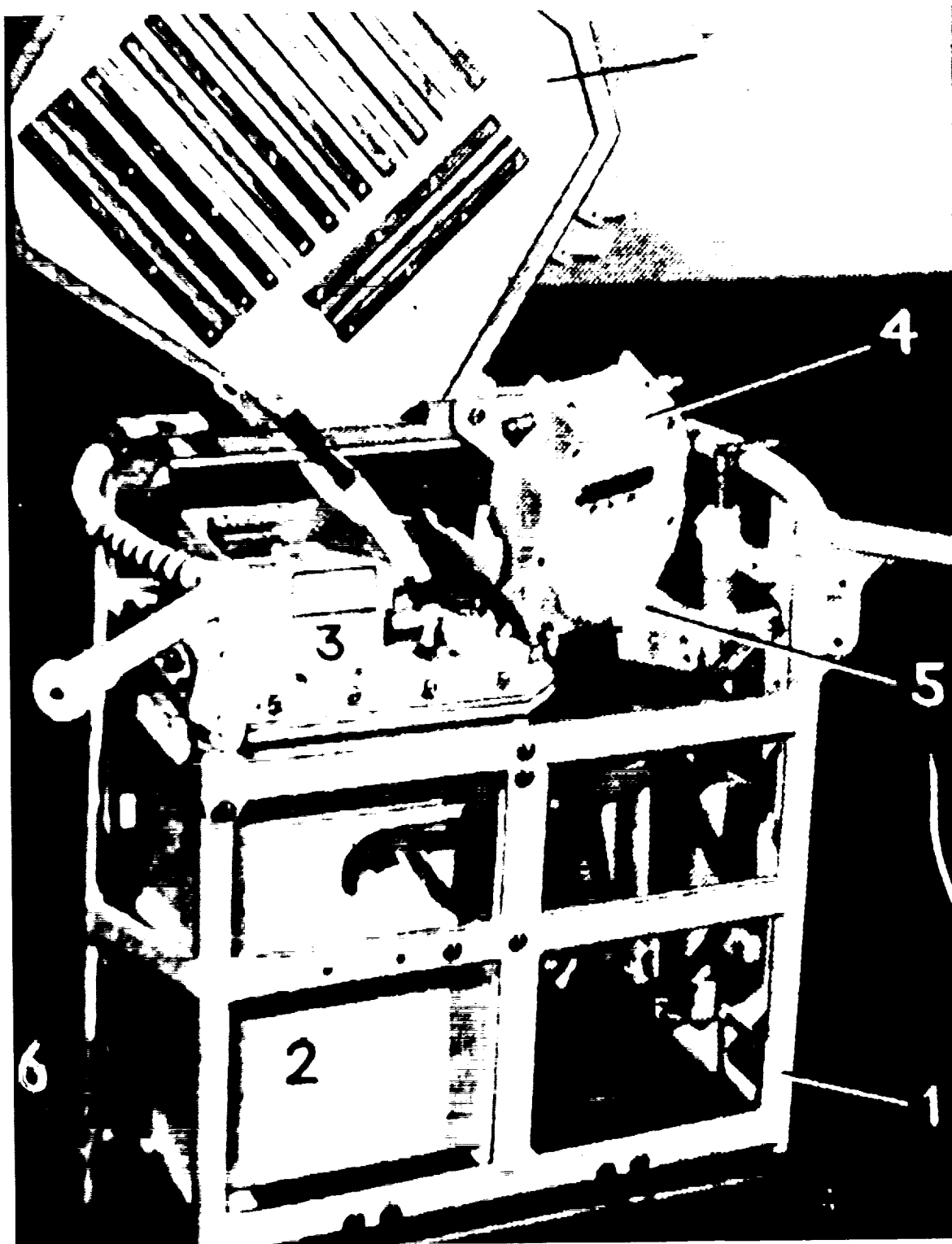


Figure 2. Workstation Used in July 1984 Soviet EVA Welding Experiment with Sample Plates Deployed

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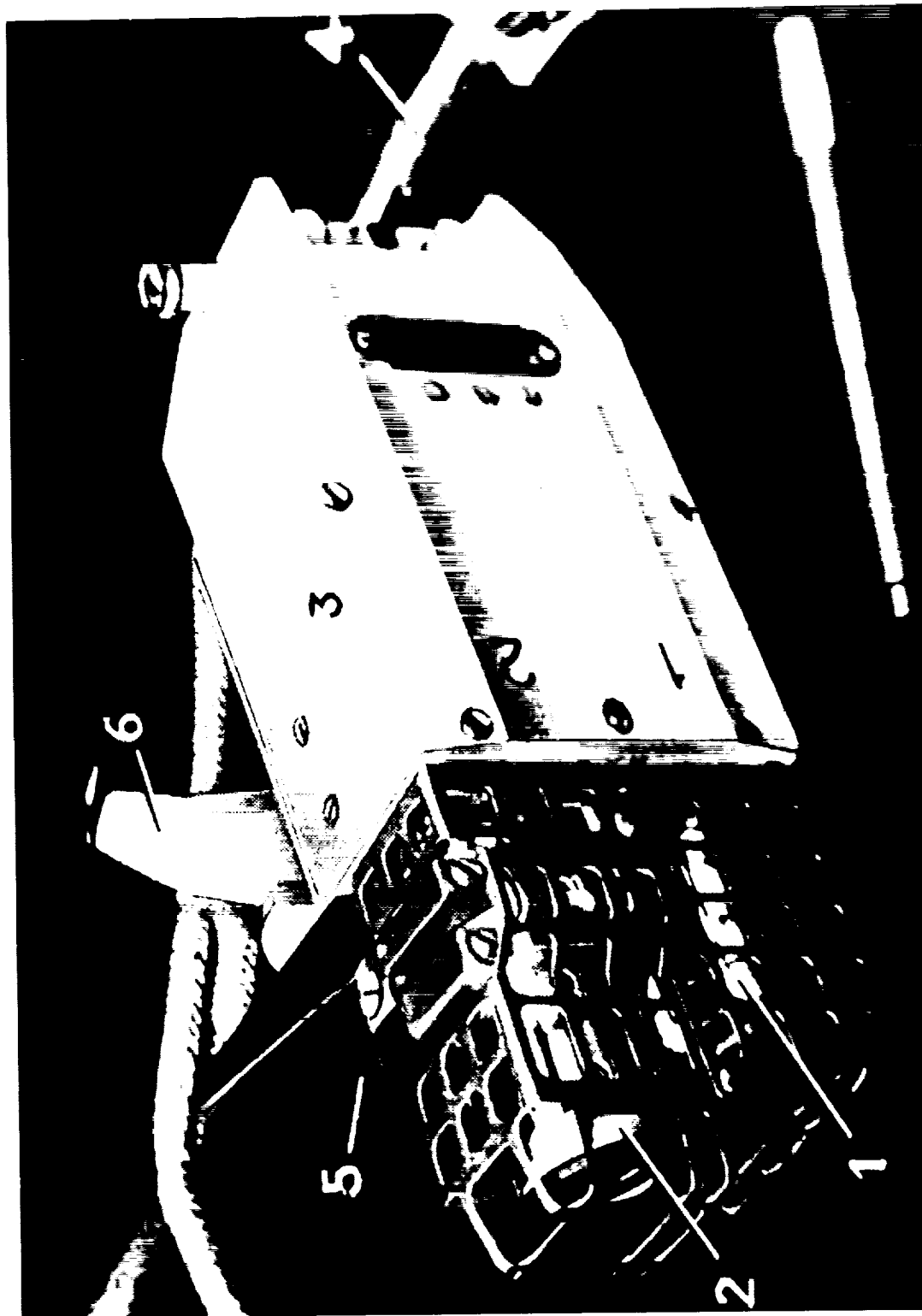


Figure 3. Multi-Purpose Electron-Beam Device Used by Soviets in On-Orbit Experiment

tance and the translation speed within allowable tolerances during manual manipulation of the gun. That such difficulties were encountered is not surprising, however, since the electron-beam process is very sensitive to these process variables. In conventional applications the electron gun or the work piece are manipulated with mechanical devices to ensure constant gun-to-work distance and steady motion. In a subsequent on-orbit test, a modified URI electron-beam gun was used to weld elements of a truss similar to those erected in the U.S. EASE/ACCESS experiment, which was performed on STS 61-B [Ref. 6].

4.4 AMERICAN TECHNOLOGY DEVELOPMENTS

In the United States, efforts to develop a welding capability for in-space operations began in the mid-1960s with the development of a hand-held electron-beam gun [Ref. 7]. This work produced a prototype device but no on-orbit testing was accomplished. Later, during the Skylab program, a series of electron-beam welds were made in the M551 experiment [Ref. 8]. This experiment demonstrated the feasibility of welding in a low-gravity, vacuum environment with no apparent seriously deleterious effects on the resulting weld. Since that time, however, there has been no development of an operational capability and, until recently, experimental work has been minimal.

In 1986 Rocketdyne began development, with IR&D funding, of a modified GTAW process for use in space. Based on extensive experience with conventional GTAW in the fabrication of the Space Shuttle Main Engine (SSME), it was felt that this process could see wide-ranging applications for assembly and repair of space structures. Particularly attractive was the mature state of the technology for making very precise, leak-free joints in fluid lines during final assembly, i.e., in-place tube welding. The only hindrance to the use of conventional GTAW in space was the inability to maintain a stable arc in vacuum. This roadblock was circumvented by modifying the nonconsumable tungsten electrode. It was discovered that by boring a small axial hole through the tungsten and then supplying inert gas through this hole, to be emitted at the electrode tip, it is possible to maintain a stable arc in a vacuum. Furthermore, since protection of the electrode and the workpiece from oxidation is not required in a vacuum, only that small amount of gas required for arc stabilization (<28 L/h) is consumed by the process. It was also found that for a given welding current and electrode-to-work distance the weld produced is both deeper and wider than that produced by conventional GTAW—indicating that process efficiency is increased. Development of this process has continued as part of Rocketdyne's internally funded programs.

4.5 REQUIREMENT FOR AN EVA EXPERIMENT

Now that the need for welding capabilities in space has been recognized and the feasibility of the candidate processes has been demonstrated, the next step in the development of an operational capability is the performance of an in-space experiment. A variety of questions arising from the operational constraints imposed by the space environment must be answered. Critical among these is the ability of an astronaut to effectively perform welding tasks when working in a pressure suit and in low-gravity. The interaction of the man with the

process as well as the allowable working envelope under these conditions must be explored. The design of the welding equipment for use by an individual whose visibility, mobility, and dexterity are restricted by a pressure suit must be addressed. The proper operation of the equipment in a combined vacuum/low-gravity environment must be evaluated. Finally, the interaction of the material being welded with the welding process in the vacuum/low-gravity environment must be assessed.

It is certainly possible to produce high-quality vacuum conditions on Earth and brief periods of low-gravity can be experienced on aircraft or sounding rockets. It is not, however, possible to produce a combined vacuum/low-gravity environment in which a human test subject can work for an extended period of time. Such an environment is currently available only in low-Earth orbit. The objective of the project discussed in this report was to define an experiment, to be performed in low-Earth orbit, which will produce the data necessary to answer the questions enumerated above.

5.0 EXPERIMENT DEFINITION PROCEDURE

The stated objective was accomplished through the performance of six tasks. These were:

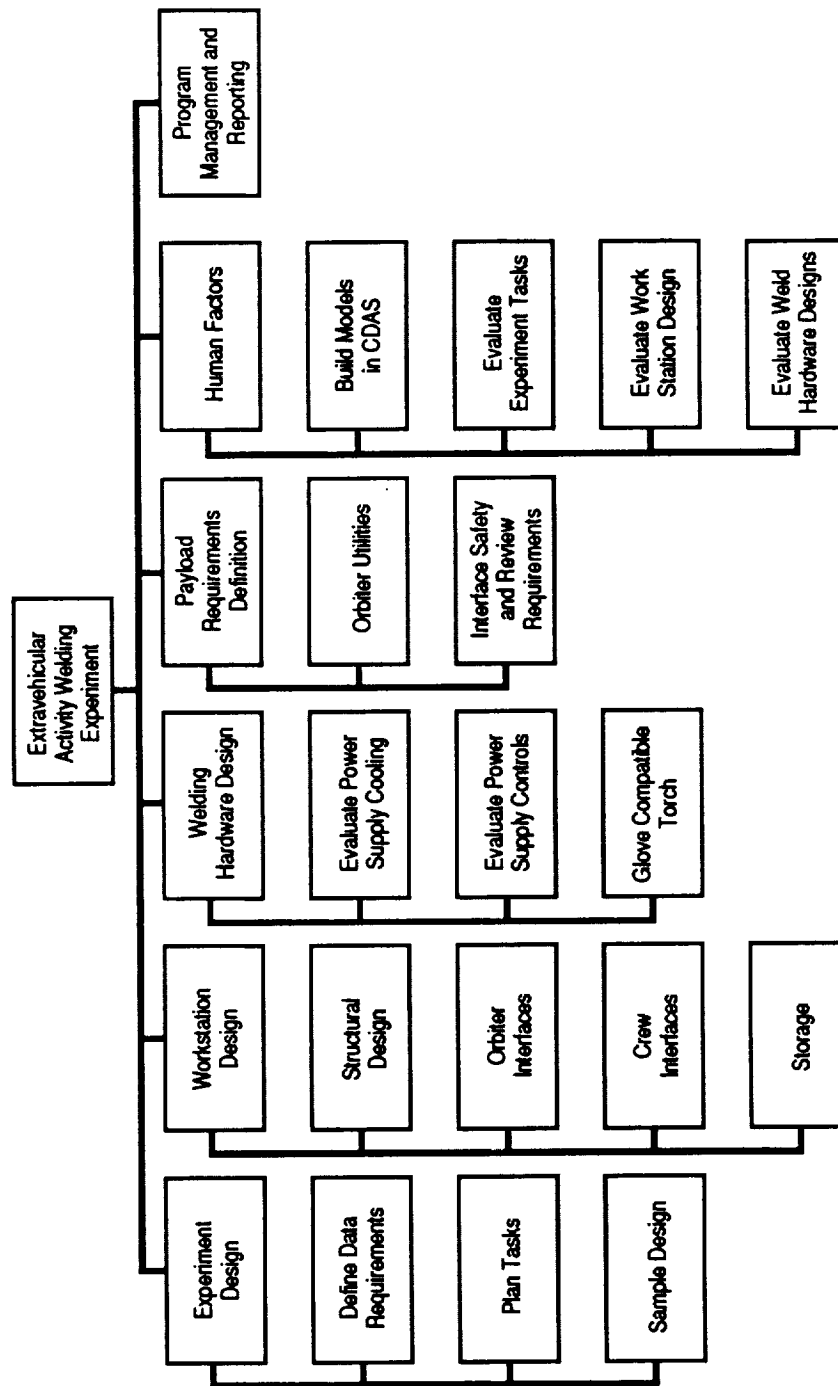
- Task 1. Experiment Design
- Task 2. Work Station Design
- Task 3. Welding Hardware Design
- Task 4. Payload Requirements Definition
- Task 5. Human Factors
- Task 6. Program Management and Reporting.

The Work Breakdown Structure (WBS) which served as a framework for the structure of this project is shown in Figure 4.

The cornerstone of this project was the design of the experiment. Of foremost importance was a clear and detailed definition of the data, which must be obtained from an eventual flight experiment to permit evaluation of the feasibility of performing manual welding tasks in an EVA environment. Based on these data requirements the following items were determined: (1) flight experiment tasks, (2) flight experiment sample requirements, and (3) flight experiment equipment requirements. The hierarchical nature of this analysis is depicted in Figure 5.

The remainder of the project tasks shown on the WBS were completed through engineering evaluations, discussions with NASA and industry experts, accumulation of relevant NASA documents, and experimental activities.

Attention is drawn to Subtask 5.1 of the WBS, designated "Build Models in CDAS." The acronym CDAS refers to a Rockwell-developed computer-aided design capability known as Core, Design, Analysis, and Simulation. Through the use of this software it was intended that models of the on-orbit workstation would be developed and coupled with models of astronauts to allow human factors simulations of the experimental tasks. However, as a result of Corporate reorganizations, the CDAS capability became unavailable to this project. To compensate, increased emphasis was placed on review of developing program plans by the Astronaut Office at NASA-JSC and on experimental low-gravity tests performed on board the NASA KC-135 research aircraft. Additional human factors data will be accumulated through limited neutral buoyancy tests planned as part of Rocketdyne's FY89 internally funded program. These tests are described in more detail in Section 7.2 of this report.



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Figure 4. Work Breakdown Structure for Extravehicular Activity Welding Experiment Definition Project

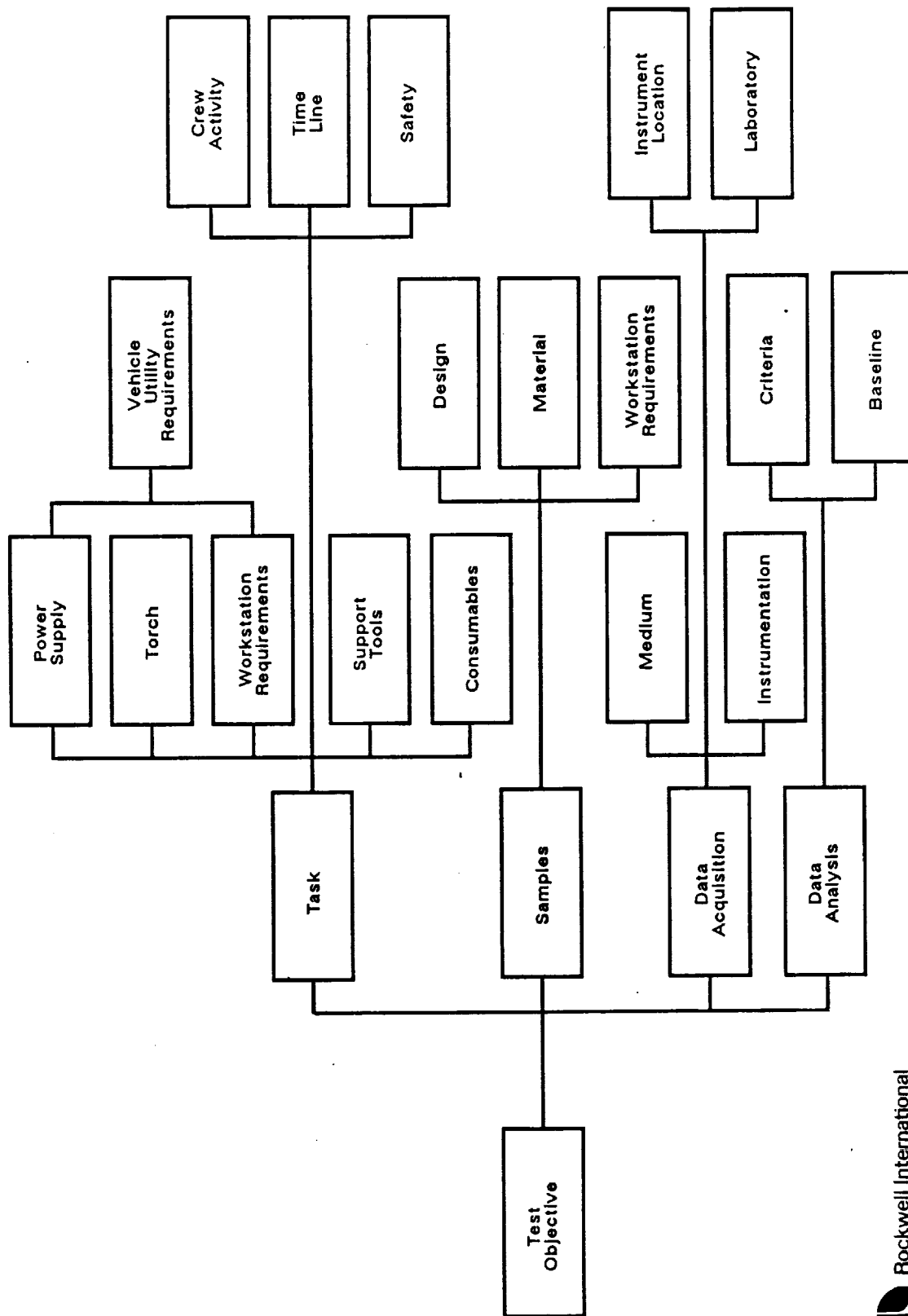


Figure 5. Hierarchical Analysis Approach Used for Experiment and Requirements Definition

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6.0 RESULTS OF EVA WELDING EXPERIMENT DEFINITION

6.1 RATIONALE FOR SELECTION OF THE GTAW PROCESS

The inherent attractiveness of welding for in-space applications arises from the versatility which it offers for planned assembly, anticipated repairs, and contingency repairs. It is important that a process be selected which provides the flexibility to perform all of these functions. Gas Tungsten-Arc Welding has been chosen as the process for use in the EVA Welding Experiment. A detailed comparative evaluation of competing candidate processes is presented in Appendix 1. In short, however, the GTAW process offers the following advantages:

- Operation in both the vacuum environment of EVA and the pressurized intravehicular activity (IVA) environment is possible
- Relatively wide tolerance in process variables (travel speed, cross-seam position, and electrode-to-work distance) enable manual operation
- Process is easily automated when desired
- Minimal safety hazards associated with the process

(By contrast, a mechanical failure during an early Soviet EBW experiment resulted in the beam partially penetrating the wall of the spacecraft. Penetration was prevented, presumably, by the bending of the beam by the Earth's magnetic field.)

- GTAW can weld all common aerospace alloys
- Technology maturity
- GTAW is widely used for in-place tube welding.

6.2 FLIGHT EXPERIMENT DESIGN - TASK 1

6.2.1 Flight Test Objectives

The first step towards developing the flight experiment requirements consisted of defining the questions to be answered by the experiment. After some iteration, these questions evolved into a set of twenty-nine test objectives. These test objectives can be classified into the following five categories: (A) Crew Considerations; (B) Crew/Process Interaction; (C) Crew/Equipment Interaction; (D) Equipment Considerations; (E) Process/Material Interaction. The complete set of test objectives is listed below.

A. Crew Considerations

1. Determine the allowable orientations for flat plate welding.
2. Determine the allowable orientations for manual welding of tubes.

3. Evaluate the capability of an EVA crewmember to adequately track linear and circular joints.
4. Determine the learning curve for manual linear welding.
5. Assess the effects of crew fatigue on welding performance.

B. Crew/Process Interactions

1. Evaluate the capability of an EVA crewmember to strike an arc.
2. Evaluate the capability of an EVA crewmember to maintain a stable arc.
3. Evaluate the need for mechanical aid for an EVA crewmember to maintain adequate torch-to-work distance.
4. Determine the optimum welding velocity for manual linear welding in EVA.
5. Assess the adequacy of weld penetration consistency.
6. Determine whether the use of pulsed current welding reduces velocity control problems during manual EVA welding.
7. Determine whether Class I quality welds can be made manually in EVA.
8. Assess the capability of an EVA crewmember to effectively do manual filler wire feed with hand-held feeder.

C. Crew/Equipment Interactions

1. Evaluate the visibility of power supply controls, markings, and displays.
2. Evaluate the EVA compatibility of welding power supply controls.
3. Evaluate manual current control during EVA welding.
4. Assess the capability of an EVA crewmember to install a filler metal insert for in-place tube welding.
5. Evaluate the design of an in-place tube weld head for use by an EVA crewmember.

D. Equipment Considerations

1. Determine the adequacy of power supply cooling.
2. Determine the adequacy of weld torch cooling.
3. Evaluate the operation of the in-place tube weld head in EVA.

E. Process/Material Interactions

1. Compare weld bead cross-section profile with previous experiments.
2. Evaluate the effect of the EVA environment on the microstructural morphology of welds in Aluminum, Stainless Steel, Inconel, and dispersion-strengthened (DS) nickel.
3. Evaluate the effect of the EVA environment on microsegregation in welds in Aluminum, Stainless Steel, Inconel, and DS nickel.
4. Evaluate manual current control versus preset current control.
5. Evaluate the effect of the EVA environment on the mechanical properties of welds.
6. Evaluate the corrosion resistance of EVA welds.
7. Evaluate the hydrogen environment embrittlement resistance of EVA welds.
8. Evaluate the capability to make Class I welds automatically in EVA.

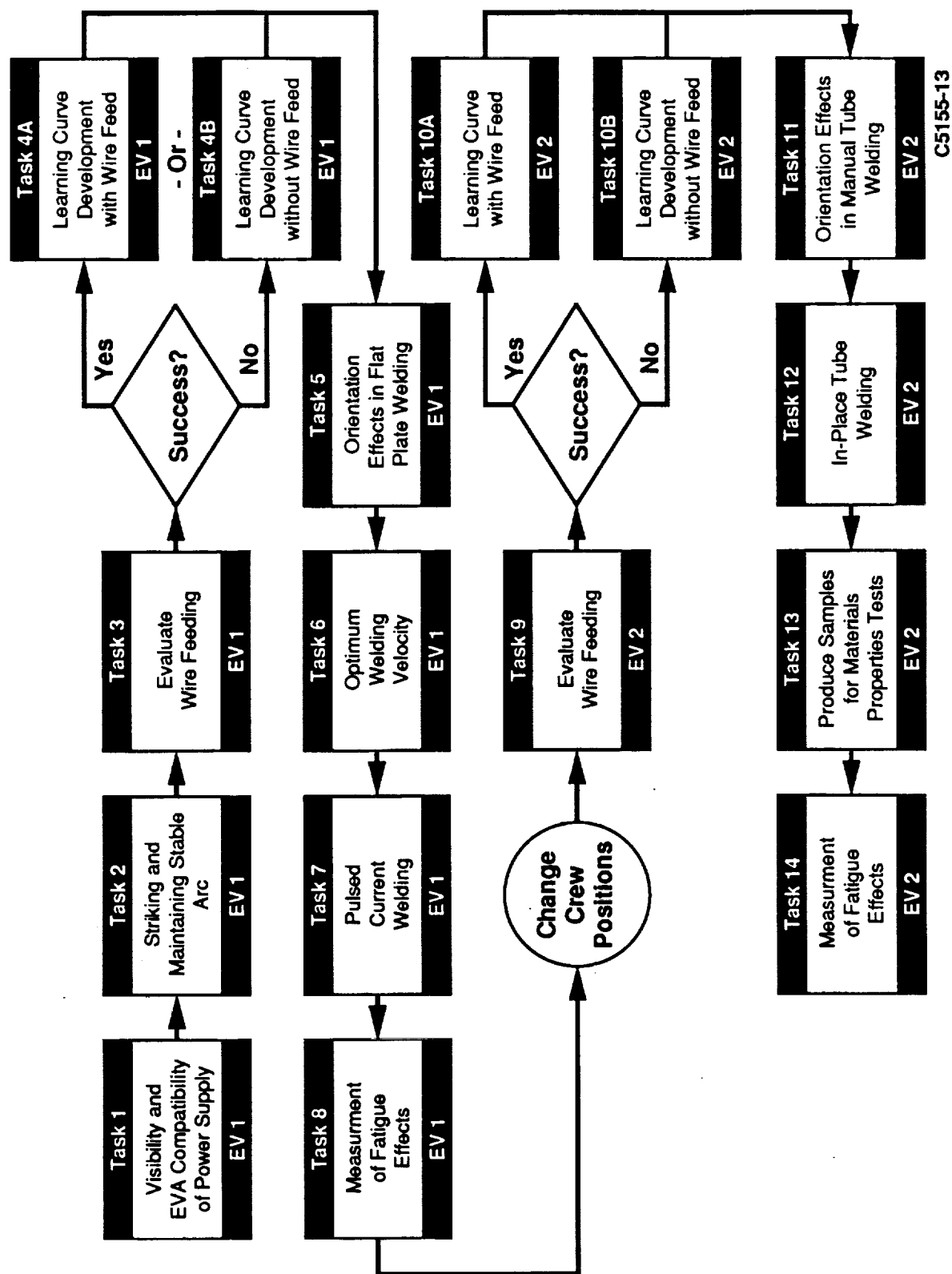
6.2.2 Flight Test Procedures

6.2.2.1 Flight Test Task Overview. A total of 14 experimental tasks have been developed. The performance of these tasks will generate the data necessary to satisfy the test objectives. The flow diagram presented in Figure 6 illustrates the sequence for the tasks. A descriptive synopsis of each task is provided in the following section. Detailed functional flow diagrams for each task are provided in Appendix 2.

The experiment begins with two simple tasks in which one EVA crewmember (designated EV1), who has assumed the role of test subject, verifies that the welding power supply is functioning properly (Task 1) and that he is able to initiate and maintain a stable welding arc (Task 2). The second EVA crewmember, EV2, will be serving in a supporting role. EV1 will continue to act as the test subject and EV2 will perform supporting functions through Task 8.

EV1 will then evaluate the feasibility of performing a two-handed task in which he adds filler metal to a weld during the welding process (Task 3). Next, he is given an opportunity to become accustomed to the environment and to working in the pressure suit by making a series of 24 simple linear welds in Task 4. Postflight analysis of these welds will provide the data necessary to evaluate the learning curve for this operation. Whether filler metal is added during these welds will depend on the results of the previous task.

In Task 5, EV1 will make another series of welds in various orientations to define the effective working envelope for welding tasks. While these tests will be performed within the optimum two-handed EVA work envelope defined in NSTS 07700, Volume XIV, Appendix 7, it is anticipated that welding in some orientations will be easier than in others due to the



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Figure 6. Sequence of EVA Welding Experiment Tasks

manipulative requirements of the welding process and the manipulative constraints imposed by the Extravehicular Mobility Unit (EMU).

The influence of the pressurized EMU on the test subject's ability to control the relative velocity between the torch and the workpiece will be analyzed through Task 6. Velocity is a critical welding process parameter. The difficulty of maintaining proper relative velocity may be relieved by using pulsed-current welding. In this case, rather than moving the torch at a smooth steady rate, the test subject would move the torch incrementally during the low current portion of the pulse cycle. The effectiveness of this technique will be evaluated in Task 7. The effects of fatigue arising from working in the EVA environment will be assessed in Task 8 by making another series of welds similar to those made in the development of the learning curve.

At this point, the crewmembers will change roles, with EV2 becoming the test subject and EV1 performing support functions. Through the use of two test subjects, the influence of individual skill on the overall results of the experiment will be minimized.

EV2 will perform Task 9 to allow him to evaluate the feasibility of wire feeding. In Task 10 he will produce samples for the generation of a second learning curve and to develop proficiency.

In Task 11, EV2 will attempt to make manual welds in small diameter tubes. This will be followed, in Task 12, with an exercise in automated in-place tube welding. With this technique EV2 will attach a welding mechanism to the tube assembly. The welding will be performed by the mechanism and control of the process will be exercised by the computerized welding power supply.

EV2, in Task 13, will set up and operate a mechanical device which will produce linear welds in flat plate samples. These welds will be used for postflight mechanical properties testing. Eliminating the variability associated with manual welding is essential for a valid evaluation of the influence of the environment on the process/material interactions. Finally, in Task 14 another series of linear manual welds will be made by EV2 for assessment of fatigue effects.

Throughout the experiment, the crewmember serving in the supporting role will be responsible for moving the sample holding frames to and from stowage and for helping to secure them in the work station holding fixture. He will be the crewmember with primary responsibility for operation of the welding system via the remote control pendant. He will also perform a safety function by observing the test subject during welding tests.

6.2.2.2 Task Synopses. The following paragraphs provide brief descriptive synopses of each experimental task.

Task 1. In this task the crewmember will evaluate the visibility of the power supply controls and displays and the ability to operate the controls. The crewmember will turn the power supply "ON" but no welding will be done in this task.

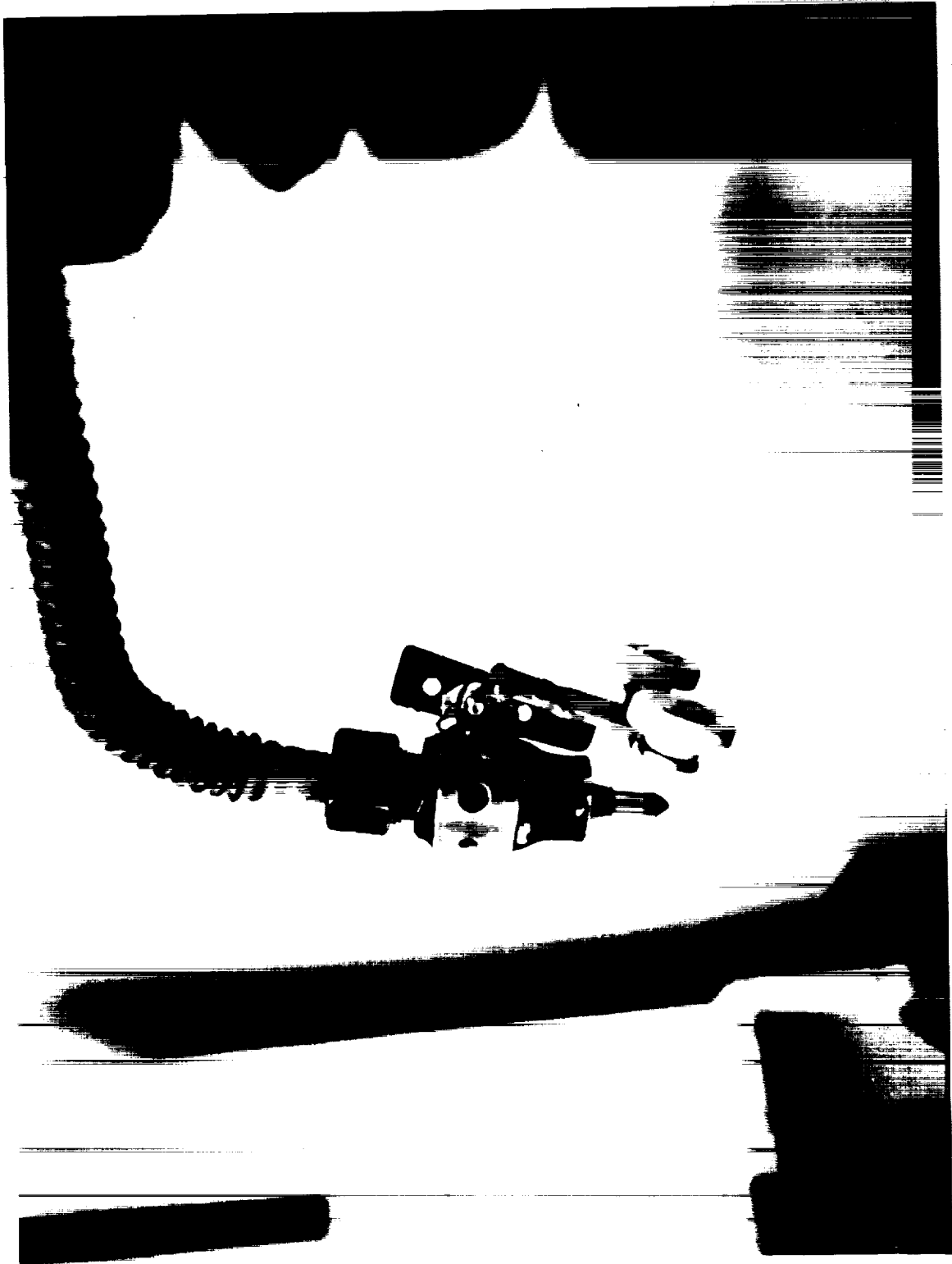
Task 2. In this task the crewmember will test the capability to strike a welding arc and maintain a stable welding arc on three metals (304L stainless steel, Inconel 718 iron-nickel superalloy, and 2219 Aluminum alloy).

Task 3. Many welding applications involving sections thicker than 0.318 cm require edge preparations and the addition of filler metal. In this task the crewmember will weld two samples. Each sample will be 25.4 cm long and 0.635 cm thick, requiring multiple weld passes to fill the joint. One weld will be done with constant welding current. The other will be done with weld current pulsing from a high level, during which filler will be added and the torch will be stationary, to a background level during which no filler will be added and the torch will be moved a small increment. An "on-the-spot" subjective evaluation will be made by the crewmember which will govern whether filler will be added in subsequent tasks. The addition of filler is expected to be more difficult but also more representative of future welding requirements. Postflight evaluations will also be performed on the samples to obtain objective data on weld quality consistency with the addition of filler metal.

Task 4. It is anticipated that some period of adaptation will be required for a crewmember to achieve the same level of performance in the EVA environment with the combined effects of low-gravity and EMU constraint as was previously achieved in ground-based training. In this task the crewmember will make a series of 24 welds, each approximately 7.62 cm long. Whether filler metal is added will depend on the judgment made by the crewmember in Task 3. After every third sample the crewmember will provide a subjective evaluation of workload and contributing factors in the format of the NASA-TLX (described in Section 6.2.23) workload rating system. Postflight analysis of the samples will consist of measurement of a variety of geometrical parameters from the cross sections of the completed welds to assess performance consistency and how it improves with practice (learning or adaptation). The workload ratings will be correlated with the data on performance to determine how perceived workload changes with learning. A secondary result of the task will be an evaluation of the effectiveness of the cooling of the power supply and the torch. This evaluation is made possible by the large number of welds to be made.

Task 5. In this task the crewmember will make welds in each of four orientations. One linear weld will be made freehand, i.e., with no mechanical spacing aid. The second linear weld will be made with a mechanical spacing aid. An example of such a spacing aid is shown in Figure 7. The third weld will be a circular weld which will simulate a pressure vessel repair patch. This task will allow an assessment of the ability of the crewmember to weld in a variety of positions. Data will be obtained from crew subjective evaluations of the overall feasibility of the task, subjective workload measurements with NASA-TLX, and postflight geometrical data from weld cross sections.

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**Figure 7. Mechanical Aid for Establishing Proper Weld
Torch-to-Work Distance**

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Task 6. The crewmember will make welds at four travel speeds. The nominal travel speeds will be 0.09, 0.17, 0.25, and 0.42 cm/s. In practice, the welding current will be reset to require that the travel speed be modified by the crewmember to maintain proper weld penetration. Each set of parameters will be utilized twice to assess repeatability. The crewmember will be asked to provide narration of the following events: arc start, travel start, travel stop, and extinguish arc. Additional data will be obtained from videotape of the operation and from postflight cross sections of the welds.

Task 7. The constraints of the pressure suit may make it difficult for the crewmember to maintain adequate smoothness and consistency in travel velocity. The use of pulsed current will allow the operator to make a series of short discreet movements at regular time intervals. This motion may be easier for the EVA crewmember than continuous motion at constant velocity. The crewmember will weld two samples in each of four orientations. The first sample will be welded with current with a 1-s pulse period. The second sample will be welded with current with a 0.5-s pulse period. Data will be obtained from crew narration of the following events: arc start, travel start, travel start, and extinguish arc. Crew comments on relative difficulty will also be recorded. Additional data will be obtained from postflight cross sections of the completed welds.

Task 8. The purpose of this task is to determine how fatigue affects the performance of a crewmember when welding in EVA. A series of eight welds will be made just as in Task 4. Subjective workload evaluations will be made in the format of the NASA-TLX workload rating system. Postflight data indicative of operator performance will be obtained from cross sections of the welds. By comparing this data with that from the samples in Task 4 it is anticipated that the effects of crew fatigue, if present, can be quantified.

The crewmembers will exchange positions and responsibilities between Task 8 and Task 9. For the duration of the experiment, EV2 will serve as the test subject and EV1 will perform supporting functions.

Task 9. All features of this task will be the same as for Task 3 but will be performed by EV2.

Task 10. All features of this task will be the same as for Task 4 but will be performed by EV2.

Task 11. This task will help to establish the feasibility of, and the working envelope for, manual repair of propellant and utility lines. By knowing allowable orientations the feasibility of performing a particular repair may be assessed. If welding of certain configurations is not feasible, then alternative methods or procedures may be required. In this task the crewmember will make three welds. In each case, the plane of the weld will be normal to the frontal plane of the crewmember at chest level. In the first, the plane of the weld will be in a horizontal orientation with respect to the crewmember. In the second weld the plane of the weld will be inclined 45 deg. In the third weld the plane of the weld will be vertical.

Task 12. In most cases, the use of an in-place tube weld device would be preferred for assembly and repair of tubes and ducts because it would minimize crew skill requirements and provide increased weld consistency. In this task, the compatibility of the weld head design for use in EVA will be evaluated along with the ability of the crewmember to perform the necessary ancillary functions, such as placing a filler metal insert ring, attaching the device to the tube assembly, and aligning the welding electrode with the weld joint. Two tube welds will be made. The first sample will be preassembled. The crewmember's function will be to place and operate the welding device. The second sample will require assembly by the crewmember followed by placement and operation of the welding device.

Task 13. The purpose of this task is to generate the specimens that will be used in the postflight materials properties tests. Welds will be made by a semiautomatic carriage device, which will provide torch positioning and motion functions. The crewmember's function will be to place the sample holding frames in the fixture, mount the torch carriage device to the work station fixture, position the torch prior to each weld and initiate the weld cycle.

Task 14. All aspects of this task will be the same as for Task 8 but will be performed by EV2.

6.2.2.3 In-Flight Data. Data will be acquired in several forms during the on-orbit experiment. It is desirable that two views be recorded on videotape. The first will provide an overview of the work station and the activities underway. The second will concentrate on the area of the work station sample holding fixture to permit detailed observation of the welding tasks. Real-time video downlink of these same two views, as well as audio downlink, will be required for the benefit of ground personnel supporting the experiment.

Data on all of the critical welding process parameters, except travel speed, will be recorded automatically by the welding power supply's on-board computer. Travel speed will be derived from the time data extracted from recordings of crew narration and from measurements of the total distance of travel during a given weld.

Real-time audio and audio recordings will also be used for acquisition of the data required for the NASA Task Load Index (NASA-TLX) subjective workload rating system. NASA-TLX is a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration [Ref. 9]. This system was developed at the NASA Ames Research Center primarily to provide a real-time measure of workload associated with cockpit flight tasks. It has since been applied successfully to other types of tasks. It is expected that the workload perceived by the test subject will change as new challenges are presented and as adaptation occurs. The perceived EVA task workload will be correlated with the measures of performance and the measured learning curve developed from Task 4 in an effort to observe this effect. To date, there have been no reported attempts to evaluate the subjective workload associated with either EVA or reduced-gravity

tasks. The effectiveness of this methodology is currently being evaluated in the tests being conducted on the KC-135 which are described in Section 6.6.3.

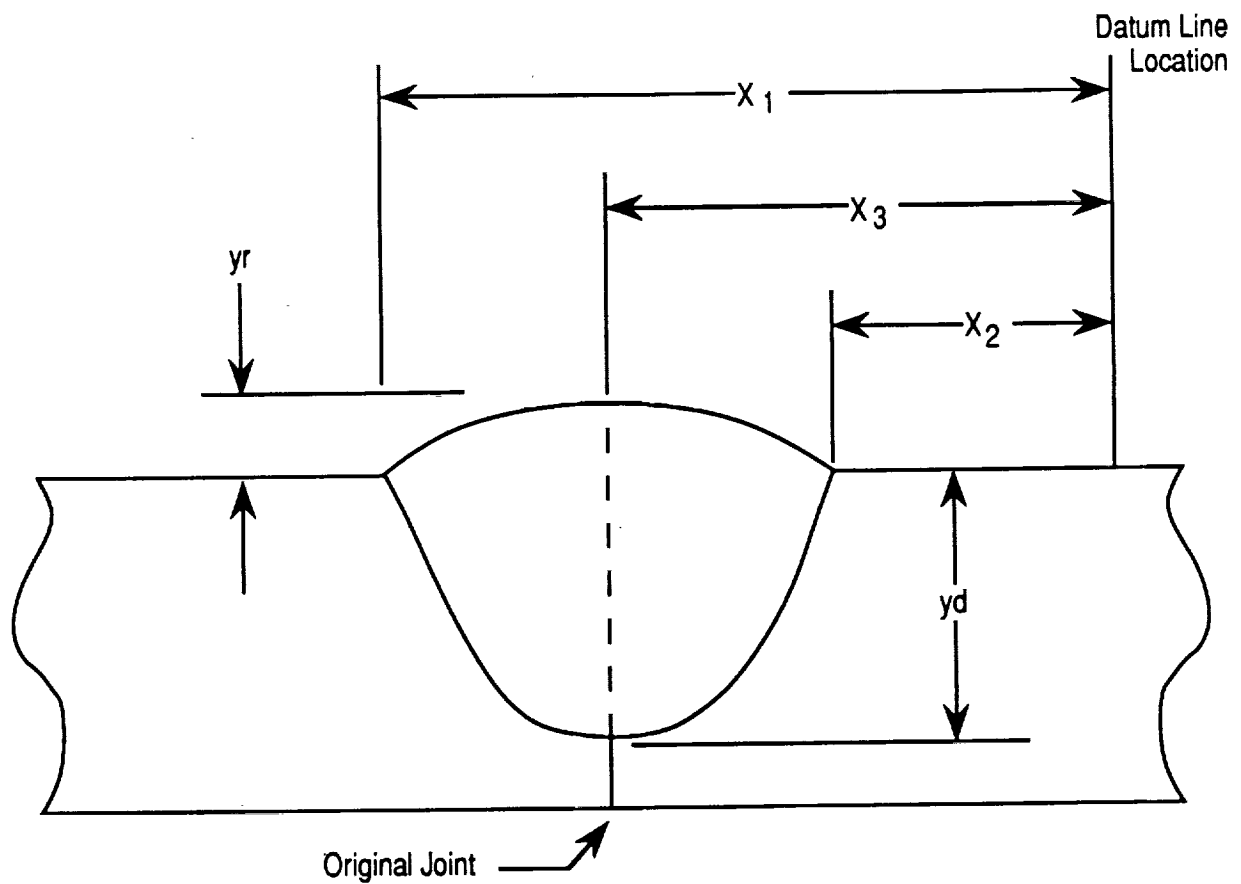
6.2.2.4 Postflight Data and Analysis. Following the flight all welded samples will be radiographed to evaluate internal weld quality and, thus, compliance with Class I weld quality requirements which define allowable internal porosity and incidence of linear defects.

Test subject performance will be evaluated from the consistency of the selected weld bead geometrical characteristics identified in Figure 8. Measurement sites will be randomly selected at several locations along the length of each weld. At each site the width of the weld bead and the location of the center of the bead with respect to the weld joint will be measured (as determined by reference to a datum line marked before flight). Welds will then be cross-sectioned at each measurement site. The height of weld bead reinforcement and depth of weld fusion zone penetration (with respect to the original plate surface) will be measured. A mean and standard deviation will be calculated for each quantity for each sample. These statistical values will serve as the basis for evaluating the performance of the test subjects. The smaller the standard deviation and the closer the mean is to a predetermined optimum value, the better the performance. These measures of performance will be used for analysis of learning curve behavior, evaluation of effective working envelopes, evaluation of the effect of weld travel speed requirements, and measurement of fatigue.

Similar data will be acquired prior to the flight through baseline experiments conducted with the flight crew during training. The flight data will be compared with the baseline data to identify any effects which may be attributed to operation in the EVA environment.

The samples produced in Task 13 to explore the process/material interactions in the EVA environment will be subjected to a full range of metallurgical examinations. Mechanical properties such as yield strength, ultimate tensile strength, ductility, and fatigue strength will be determined from large specimens cut from these samples. Metallographic cross sections will be examined to evaluate grain structure morphology and overall weld bead shape. These, or similar, sections will be examined with microanalytical tools such as the Scanning Transmission Electron Microscope (STEM) to detect possible variations in microsegregation which might be attributed to either low-gravity or vacuum. Standard corrosion and hydrogen environment embrittlement tests will be performed on selected samples, as well, to determine whether the susceptibility of welds made in the EVA environment to these effects is altered.

6.2.2.5 Task Requirements Summary. The basic requirements for each of the flight experiment tasks are summarized in Table 1. The crewmember, EV1 or EV2, serving as the test subject for each task is identified. The sample holding frames (discussed in greater detail in the next section) needed for each task are identified along with the approximate mass for each frame and the total mass of samples and frames required for the experiment. The estimated time required for the performance of each task is also provided as is the total time for the entire experiment. This information was developed through a laboratory simulation of the experiment. This simulation is discussed in detail in Section 6.6.4.



$X_3 \equiv$ bead center line location

$$X_3 = X_2 + \frac{X_1 - X_2}{2}$$

$X_\omega \equiv$ bead width

$$X_\omega = X_1 - X_2$$

$y_r \equiv$ weld bead reinforcement height

$y_d \equiv$ weld fusion zone depth of penetration

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Figure 8. Critical Weld Bead Geometrical Characteristics to be Used for Test Subject Performance Assessment

Table 1. Task Requirements Summary

Task	Test Subject	Task Time Line	Sample Frame	Mass Per Frame	Total Mass	Type Samples
1	EV1	8.08	N/A	N/A	N/A	N/A
2	EV1	19.33	1 2 3	15 kg 15 kg 14 kg	15 kg 15 kg 14 kg	304L IN718 2219Al
3	EV1	7.42	4	16 kg	16 kg	304L
4	EV1	26.67	5, 6, 7	16 kg	48 kg	304L, 8 ea
5	EV1	27.25	8, 9, 10, 11	16 kg	64 kg	304L 2 linear 1 circular
6	EV1	29.83	12, 13 14, 15	16 kg	64 kg	304L 2 ea frame
7	EV1	20.17	16, 17 18, 19	16 kg	64 kg	304L 2 ea frame
8	EV1	9.00	20	16 kg	16 kg	304L, 8 ea
9	EV2	7.42	21	16 kg	16 kg	304L, 2 ea
10	EV2	26.67	22, 23, 24	16 kg	48 kg	304L, 8 ea
11	EV2	17.92	25	12 kg	12 kg	
12	EV2	6.83	25	12 kg	12 kg	
13	EV2	12.00	26 27 28 29	16 kg 15 kg 16 kg 16 kg	16 kg 15 kg 16 kg 16 kg	304L 2219Al IN718 DS nickel
14	EV2	9.00	30	16 kg	16 kg	304L, 8 ea
Total time: 218.68 min				Total mass: 483 kg		

6.2.2.6 Baseline Data Acquisition. Baseline data necessary for thorough evaluation of the spaceflight experiment results will be acquired during the flight crew training activities. There are a variety of factors in the EVA environment which could affect the performance of the crewmember test subject. These include: mobility and dexterity limitations imposed by the EMU, operation in low-gravity, and sensitivity of the vacuum welding process. If crewmember EVA performance is degraded relative to shirtsleeve laboratory performance then identification of the cause of that degradation will be important for future on-orbit welding system development. To help isolate each of these factors and gather the most useful baseline data, experimentation and training of progressive complexity should be implemented. The following suggested training sequence serves to illustrate this concept:

- Shirtsleeve Laboratory Training. This will allow the crewmembers to gain basic proficiency with conventional GTA welding.
- Glove Box Conventional GTA Welding. This will allow the crewmembers to become familiar with performing the manipulations required for conventional GTAW when using EMU gloves with a 4.3 psi differential.
- KC-135 Shirtsleeve GTA Welding. This will allow the crewmembers to become familiar with the technique modifications necessary to allow them to weld in low-gravity.
- KC-135 Pressure-Suited GTA Welding. This will allow the crewmembers to develop techniques for working in the EMU and in low-gravity. Data from these tests will serve as the primary baseline. Data from earlier phases will be supportive.
- WETF Training. Crew evaluations from these tests will help in the finalization of the work station layout and procedure development.

6.2.3 Flight Sample Design

6.2.3.1 Samples. The samples to be used for most of the flight tasks are flat plates with linear butt joints. The reason for selecting this simple configuration was to permit isolation of the effects of the operational environment on the test subject's performance. It also allows comparison of results between tasks (e.g., the effect of pulsed current vs. constant current). However, a circular lap weld will be made in Task 5 to simulate a potential practical situation—repair of a hole in a pressure vessel. More complex samples, and greater variety of samples, would require increased welding skill on the part of the test subject and would decrease the value of intertask comparisons. Stainless steel (alloy 304L) was selected as the principle sample alloy because its terrestrial welding metallurgy has been extensively characterized and it is relatively easy to weld. Aluminum alloy 2219 was chosen for some of the Tasks because of its selection for use in the Space Station Freedom Common Module hull. Inconel 718, an iron-nickel superalloy, was also chosen for limited tests because of its widespread use in propulsion systems. A dispersion strengthened nickel alloy will be welded in Task 13 to explore the potential beneficial effects of welding this alloy in low-gravity. Terres-

trial welding of this type of material is difficult because of the tendency for the strengthening disperoids to segregate due to density differences with the base alloy.

6.3.3.2 Sample Holding Frames. It was recognized early in the process of developing the experiment support requirements that it would be very difficult for a pressure-suited crewmember to handle thin plate samples. Additionally, storage and management of a large number of small samples would not be feasible. To resolve these problems, the decision was made to mount the samples required for each discrete task or subtask in holding frames. Several additional benefits are derived from this arrangement including:

1. The crewmember will not need to handle hot samples.
2. Chances of contact with hot samples are minimized since the samples are recessed in the frame and are covered at all times except when being welded.
3. Any expulsion of metal from the back surface of a plate sample during welding will be contained by the frame.
4. The frame provides a common configuration for mounting to the work station, thus simplifying work station fixturing design.
5. The frame provides for a simple method of connecting the samples to the ground circuit.
6. The frame will eliminate exposure of the crewmember to the ground circuit except through the sample being welded.
7. The frame allows more orderly and organized stowage of samples.
8. The frame provides standard configuration hand holds for the crewmember with which to handle the samples.

The frames are somewhat complex structures. A complete set of drawings for a sub-scale prototype frame is presented in Appendix 3. While the sample configurations will differ, the layered concept for the internal structure of the frames will be common throughout. The samples are supported at their edges by a copper conductor plate. The conductor plate provides for electrical connection of the samples with the ground circuit. Access to the conductor plate is provided by a slot cut through the back plate. A spring-like contactor strip on the welding fixture connected to the ground circuit passes through the slot and contacts the copper conductor plate completing the circuit. The back plate, which is solid except for the conductor access slot, provides containment to the back side of the samples. Middle layers hold the samples laterally in position. The top plate retains the sample and contains slide-covers which are opened only during welding of the sample beneath that cover. After welding, the cover is slid back to its closed position to prevent contact of the crewmember's gloves with the hot sample.

Top views for each of the types of frames which will be required to hold the flight samples are shown in Appendix 4. The frame numbers required for each task were identified in Table 1 which appeared in Section 6.2.2.

6.3 WORK STATION DESIGN - TASK 2

The work station for this experiment will consist of the structures required to: house the experimental hardware, stow the samples before and after welding, position and hold samples during welding, provide appropriate restraint to the EVA crewmembers, and provide all necessary interfaces between the experiment and the Shuttle Orbiter. One initial concept for the work station was for the individual elements (power supply, stowage containers, welding fixture) to be mounted on a Mission Peculiar Equipment Support Structure (MPRESS). This concept was set aside, however, when it was concluded that the additional weight of the MPRESS would limit manifesting opportunities.

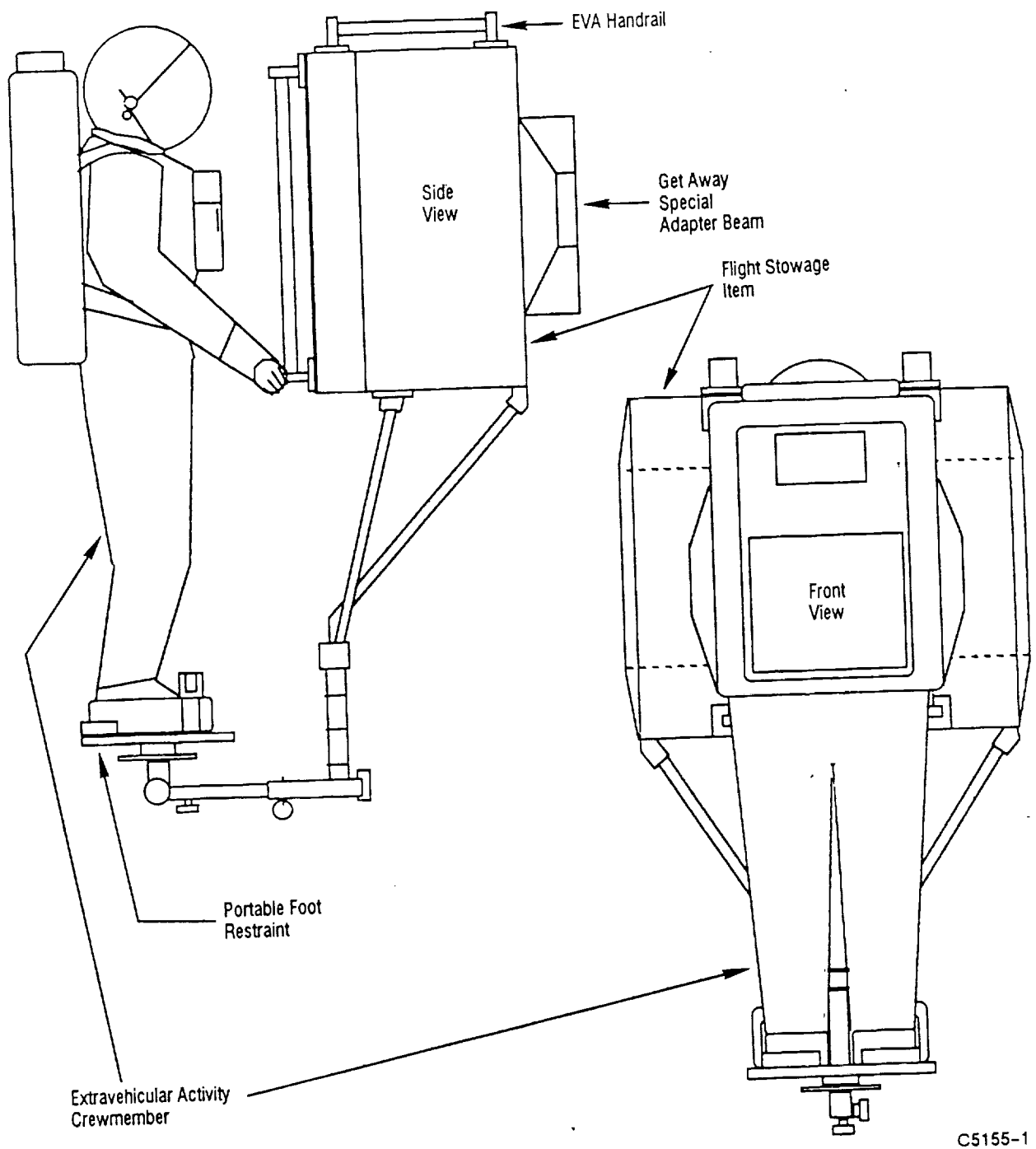
A preferred alternative concept is to place the experiment components in containers mounted to the sidewall of the Orbiter's payload bay via Get-Away Special adapter beams. The reduced total weight for the experiment and the reduced impact on payload bay cargo configuration should enhance manifesting opportunities. The MPRESS concept could be easily revitalized, however, if found to be more desirable during manifesting.

There was a strong desire in the early stages of designing the work station to maximize the use of existing flight hardware. When the sidewall mounting option was selected initial consideration was given to using the Cargo Bay Stowage Assembly (CBSA). Subsequent consultation with the NASA-JSC Crew and Thermal Systems Division [Ref.10] revealed that only one or two CBSAs exist) and that they would require extensive modifications to meet the requirements of this experiment.

Therefore, it is believed that the best course of action would be to design new flight stowage items (FSIs) for this experiment. It is anticipated that these FSIs will be GFE.

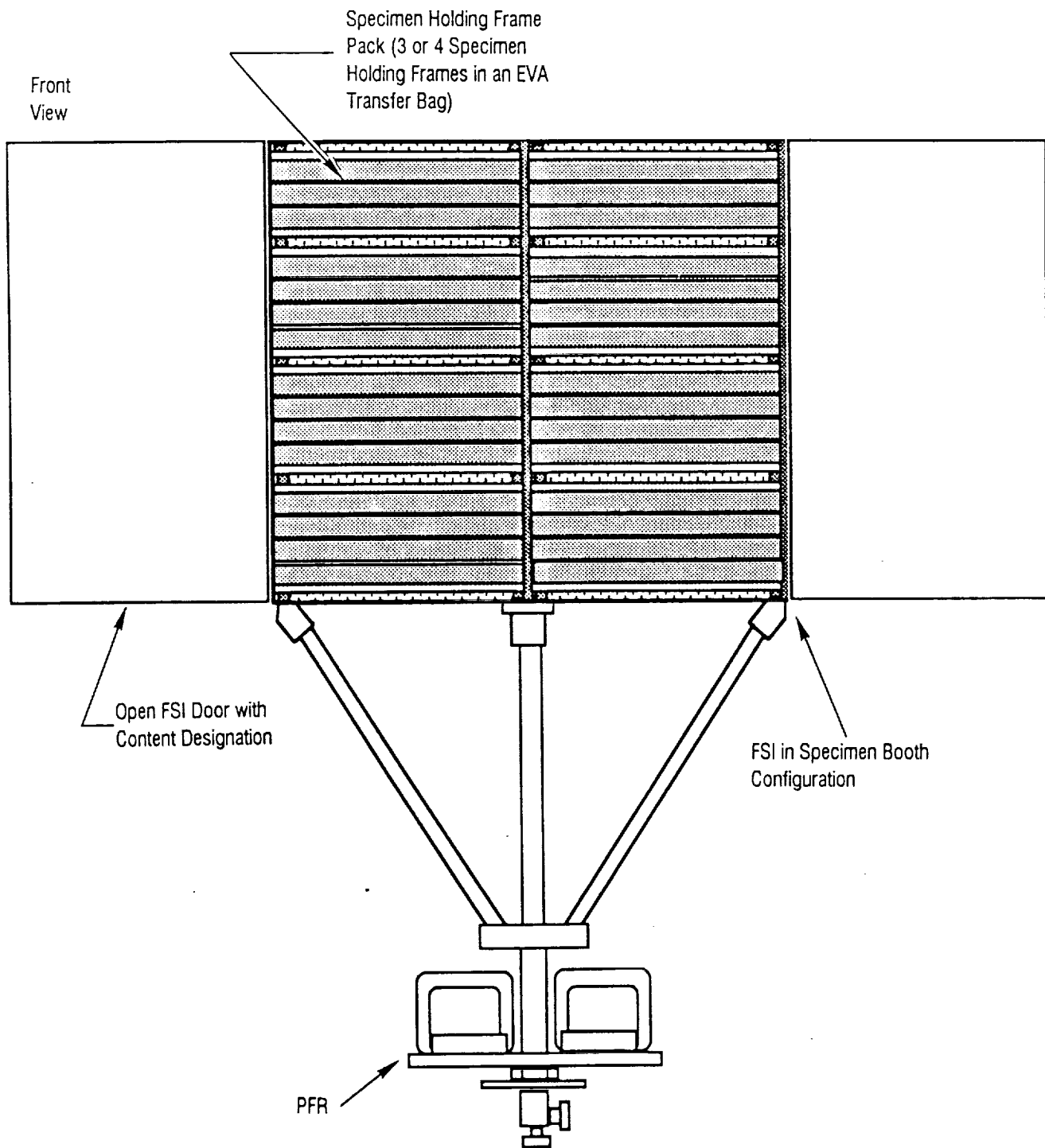
The FSIs will be similar in size and configuration to the CBSA. Conceptual designs were developed as part of this project. Figure 9 depicts the general configuration of the conceptual FSI, three of which will be required. Figure 10 shows an FSI configured for stowing samples and Figure 11 illustrates an FSI configured to hold experimental hardware and the weld sample holding fixture. Mock-ups of two FSIs in these configurations were constructed to support a flight experiment timeline simulation study (as described in Section 6.6.4). Figure 12 shows the external appearance of the FSIs mounted on the simulated Orbiter sidewall. The internal structure of the sample stowage FSI is shown in Figure 13 and that of the FSI holding the experiment hardware and the weld sample holding fixture is shown in Figure 14.

As noted in the discussions of the specific experimental flight tasks in section 6.2.2, it will be necessary to place the samples in a variety of orientations with respect to the EVA



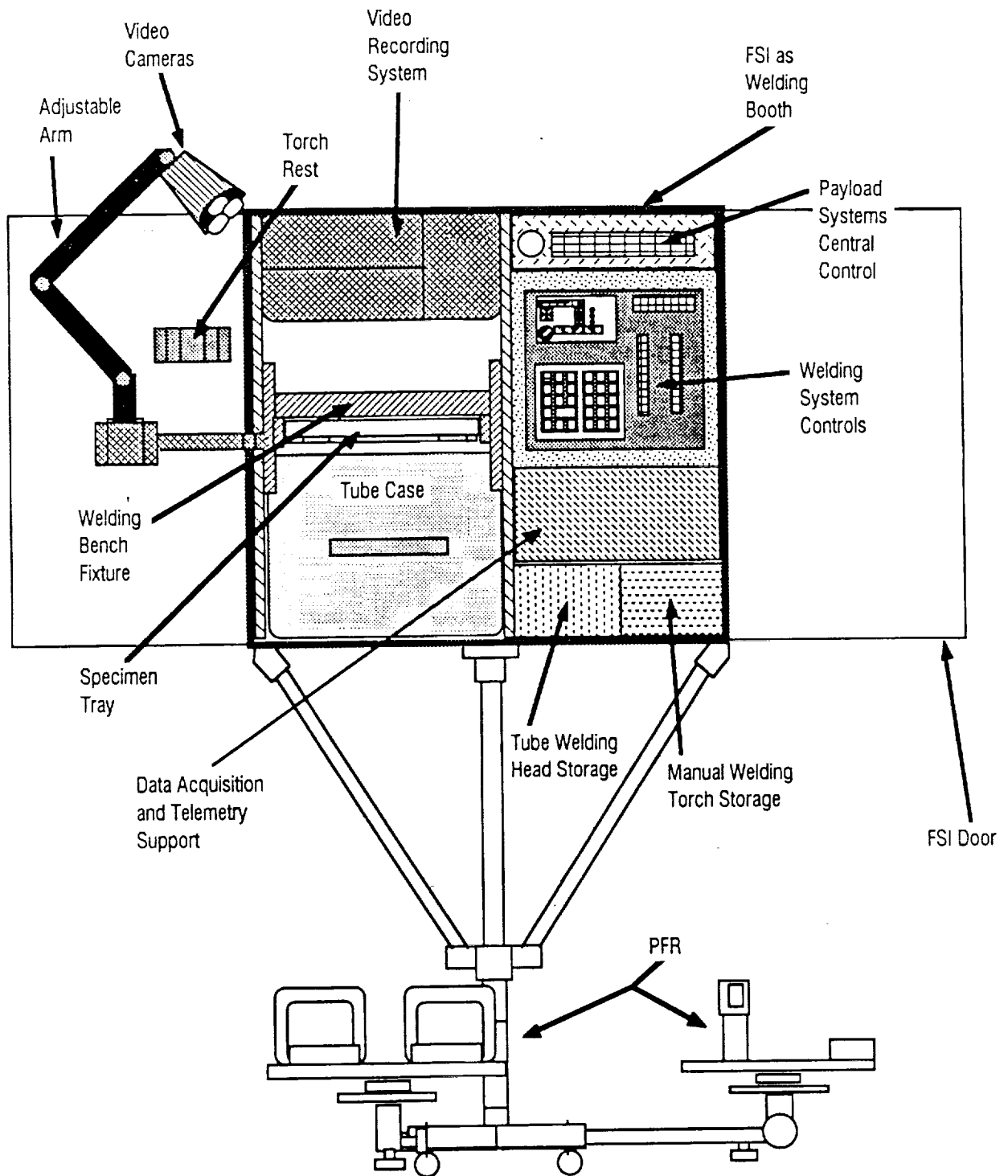
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Figure 9. Conceptual Illustration of Flight Stowage Item with EVA Crewmember in Foot Restraint



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Figure 10. Flight Stowage Item Configured for Sample Stowage



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Figure 11. Flight Stowage Item Configured to Hold Experimental Hardware and the Weld Sample Holding Fixture

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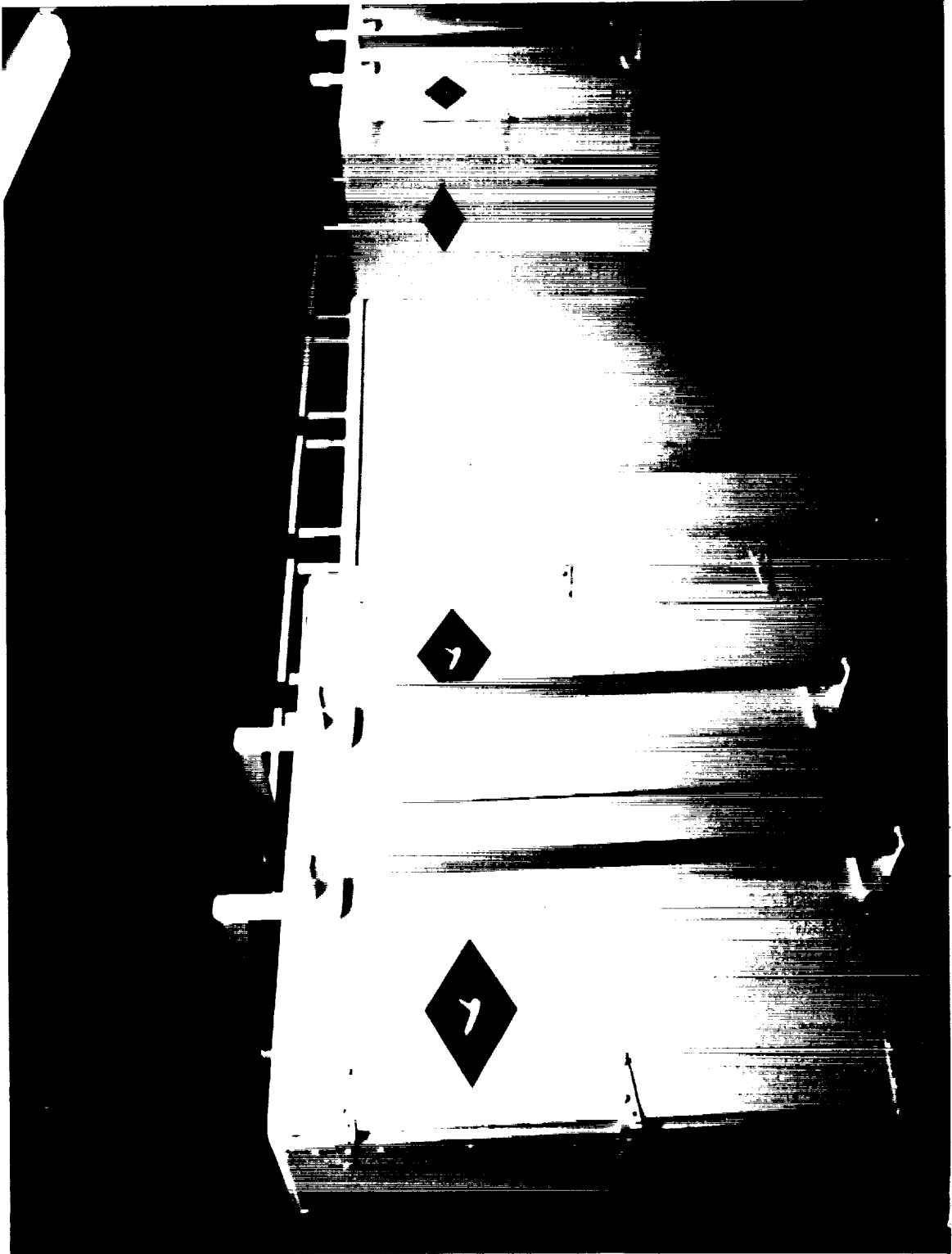


Figure 12. Mock-Up FSIs Mounted to Simulated Orbiter
Sidewall for Time-Line Study

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Figure 13. Internal Configuration of Sample Stowage FSI Mock-Up

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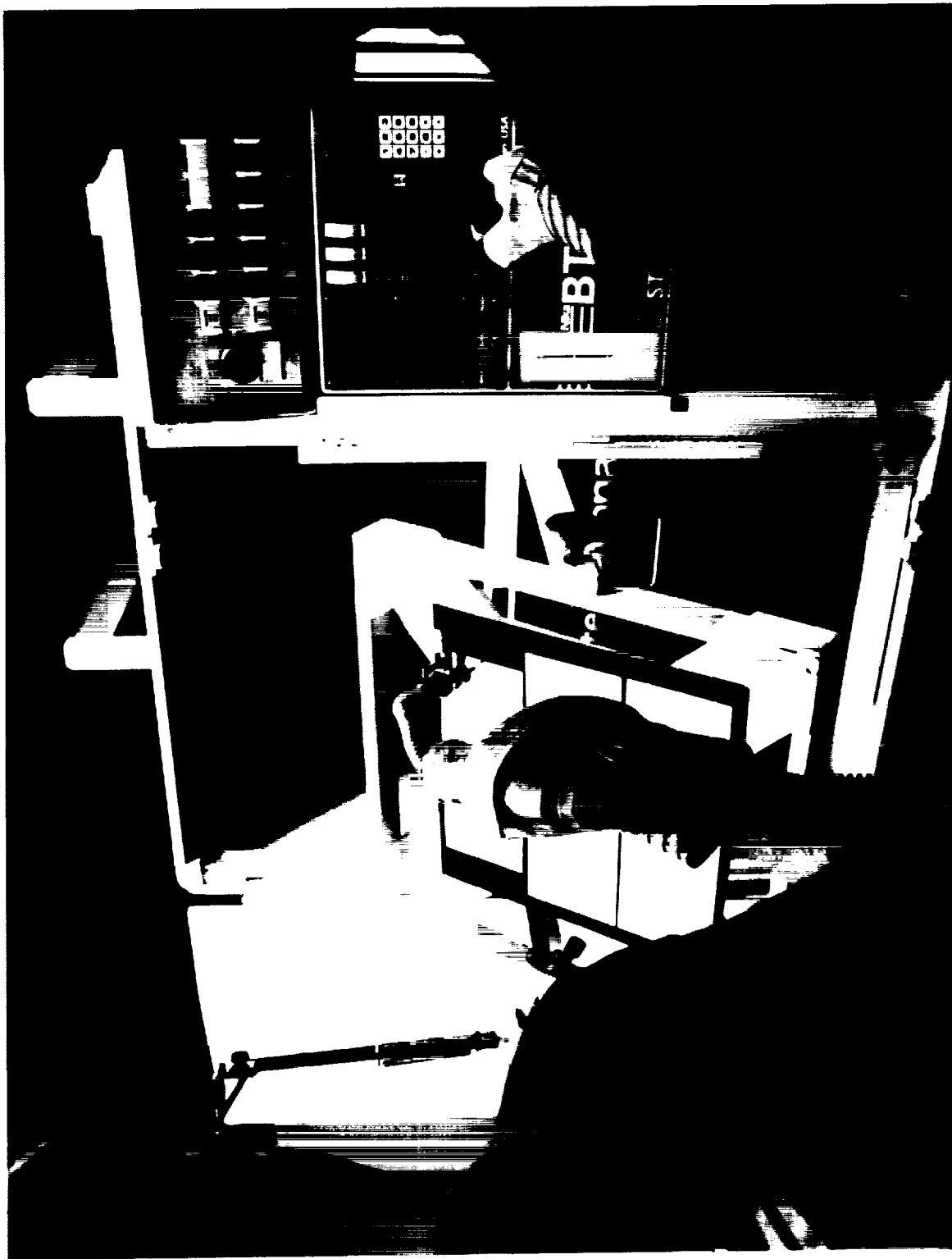


Figure 14. Internal Configuration of Welding Station FSI
Mock-Up with Welding Power Supply

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crewmember serving as the test subject, as shown in Figures 15-18. The pivot-point locus for the sample holding fixture is shown in Figure 19.

At the time that these mock-ups were fabricated and the timeline simulation was performed, the favored approach to the power supply design was to make it fully compatible with direct exposure to vacuum. The mock-ups reflect this approach in that the power supply is shown mounted in one of the FSIs. Since the time of the simulation, however, the preferred approach to the power supply design issue has shifted to placing the unit inside a pressurized environment. The reasons for this change in approach are discussed in section 6.4.1. The impact of this design change on the work station is to remove the power supply from the unpressurized FSI and to place it inside a modified Get-Away Special cannister.

The primary modification to the Get-Away Special cannister involves the fabrication of a new base plate to provide adequate feedthroughs. The feedthroughs required are for: Orbiter power in, welding power out, welding ground circuit in, Orbiter coolant, welding control interface, and wire feeder control interface.

One possible arrangement for the FSIs and the Get-Away Special cannister in the Orbiter payload bay is shown in Figure 20. Due to the distance between the sample stowage FSIs and the welding site, transportation of the samples is achieved with multiple-specimen frame packages. By moving four frames at once the amount of translation by the supporting crewmember about the payload bay is minimized.

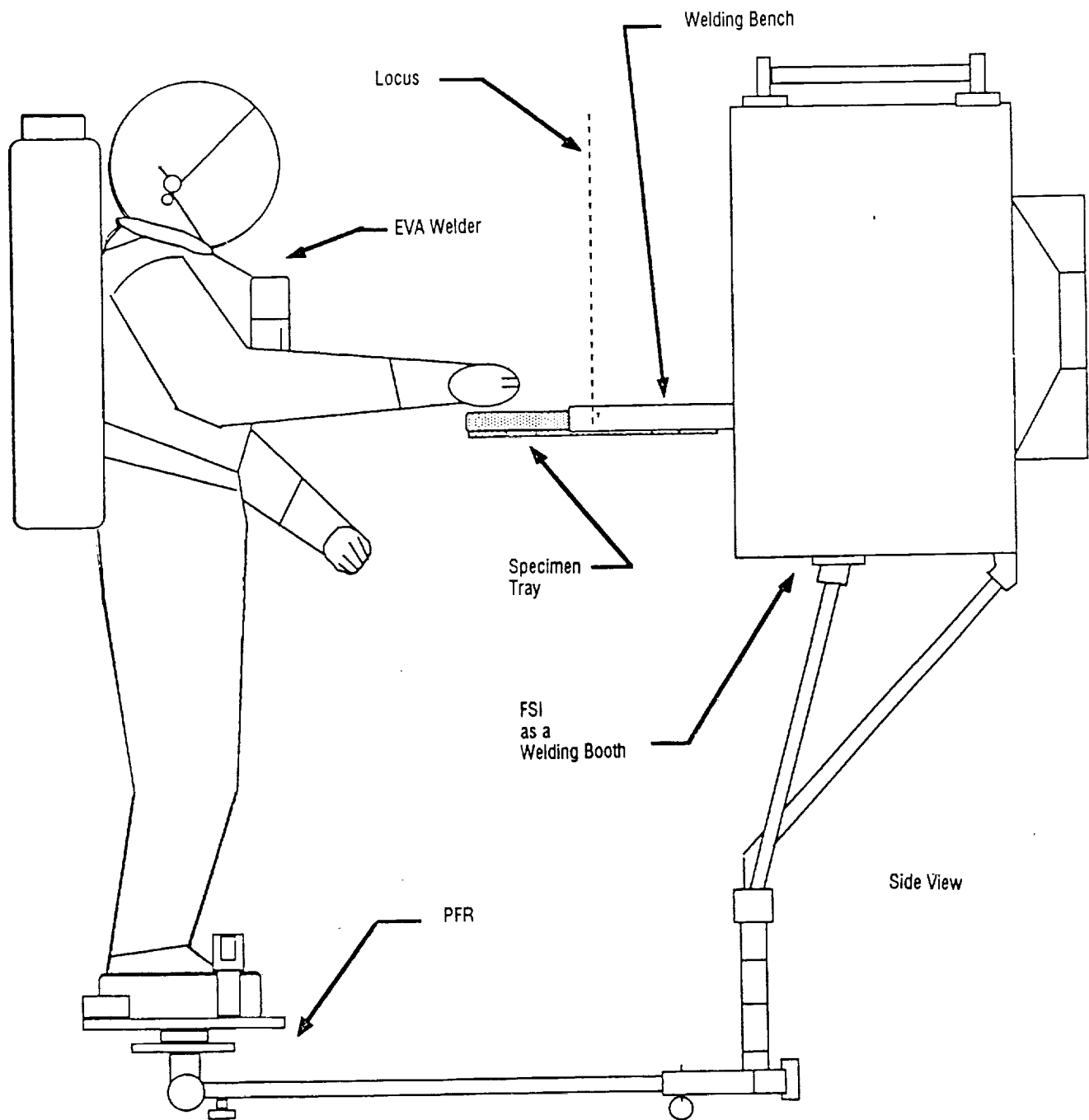
6.4 WELDING HARDWARE DESIGN - TASK 3

6.4.1 Power Supply

The purpose of the welding system is to perform GTAW in the environment of space under EVA limitations. The EVA welding experiment will implement a commercially manufactured welding system which is redesigned for compatibility with the space environment and EVA crewmembers.

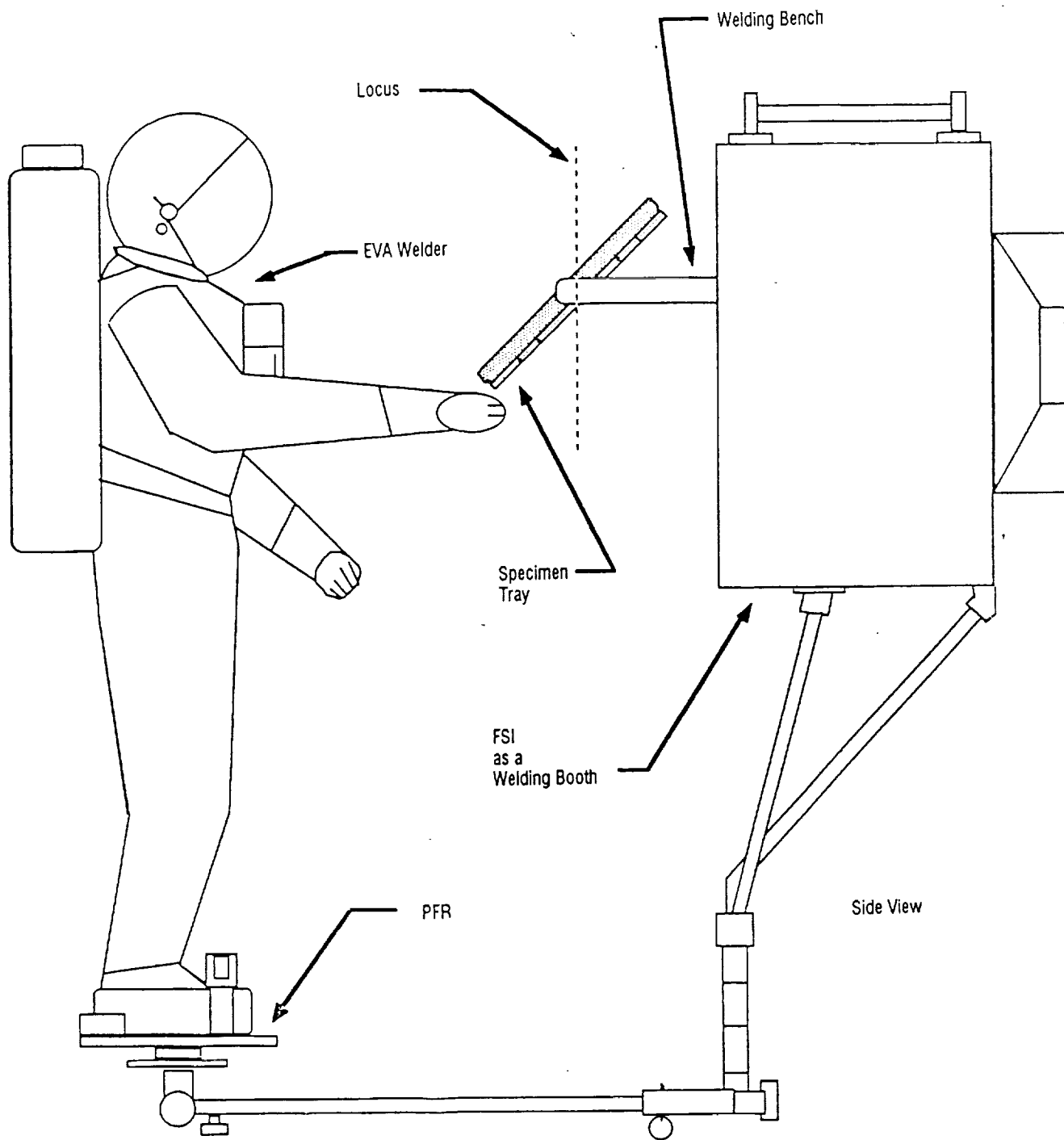
One approach considered was to modify the internal design of the welding power supply to enable direct exposure to the vacuum. The other approach is to place the power supply in a pressurized environment similar to a Get-Away Special cannister. This latter approach would produce a power supply, which does not offer all of the flexibility which is ultimately desired in a fully operational system, but it could be achieved with less modification of the power supply and, thus, for less cost.

Evaluation of commercially available power supplies showed that, to make them compatible with vacuum operation, modifications would be required to the electrical insulation, pressurized electronic components, and the temperature regulation system. All PVC electrical insulation would require substitution with appropriate non-outgassing materials such as Teflon. All pressurized electronic components, consisting mostly of electrolytic capacitors, would require replacement by vacuum-rated devices. Red-line temperature operation limits for the



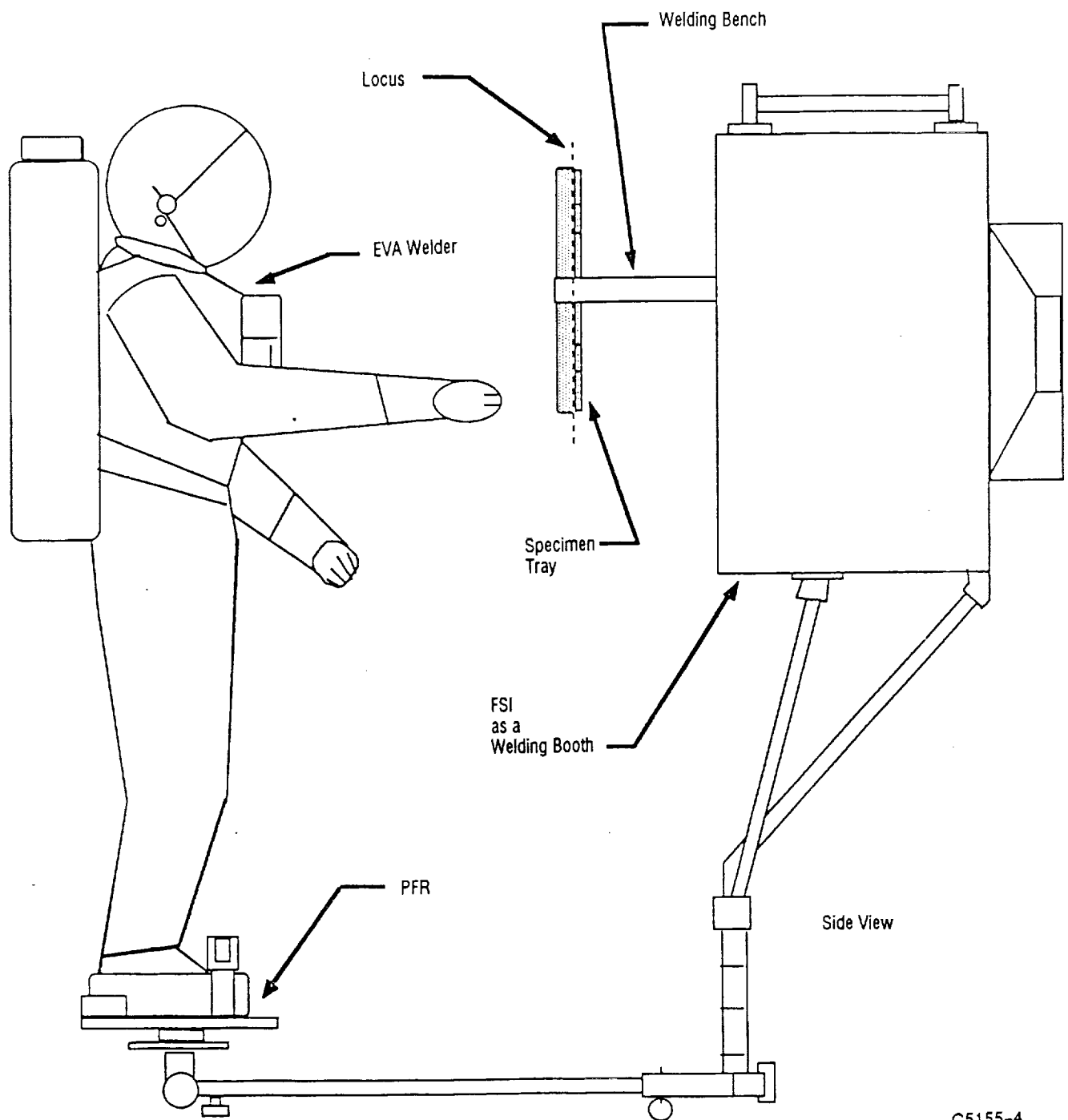
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Figure 15. Weld Sample Holding Figure in Horizontal Orientation



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Figure 16. Weld Sample Holding Fixture in 45-Degree Chest-Level Orientation



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Figure 17. Weld Sample Holding Fixture in Vertical Orientation

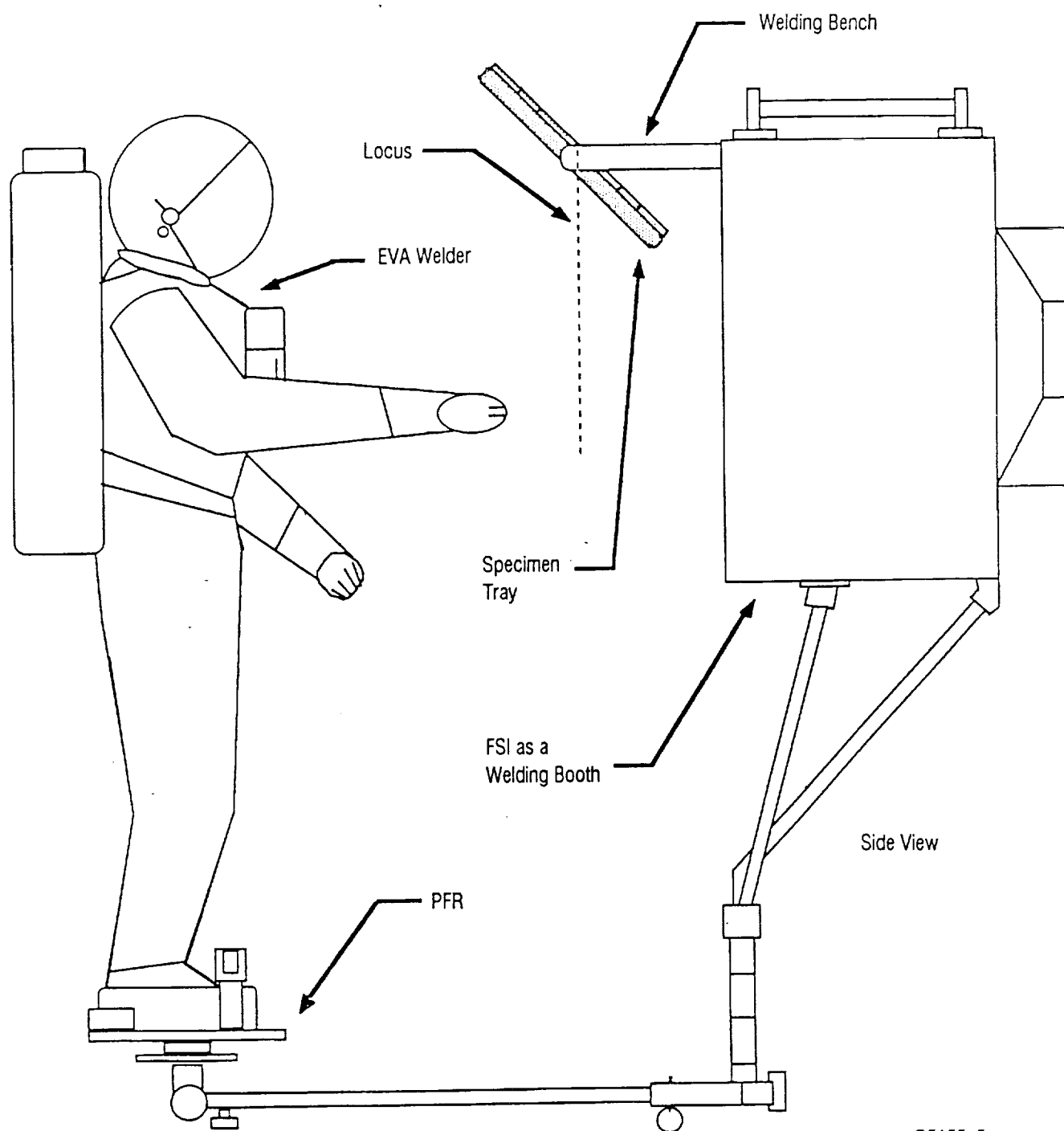
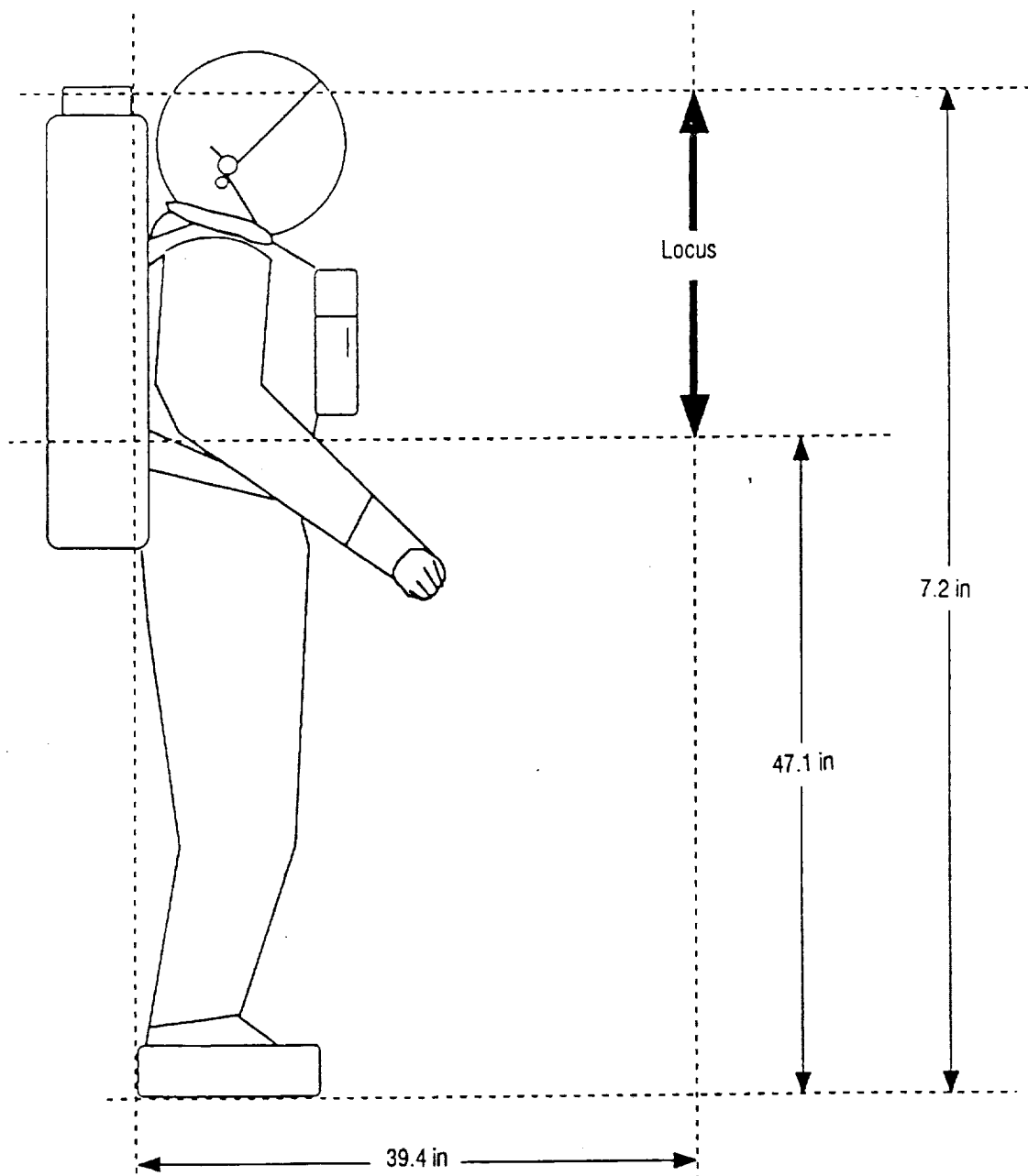
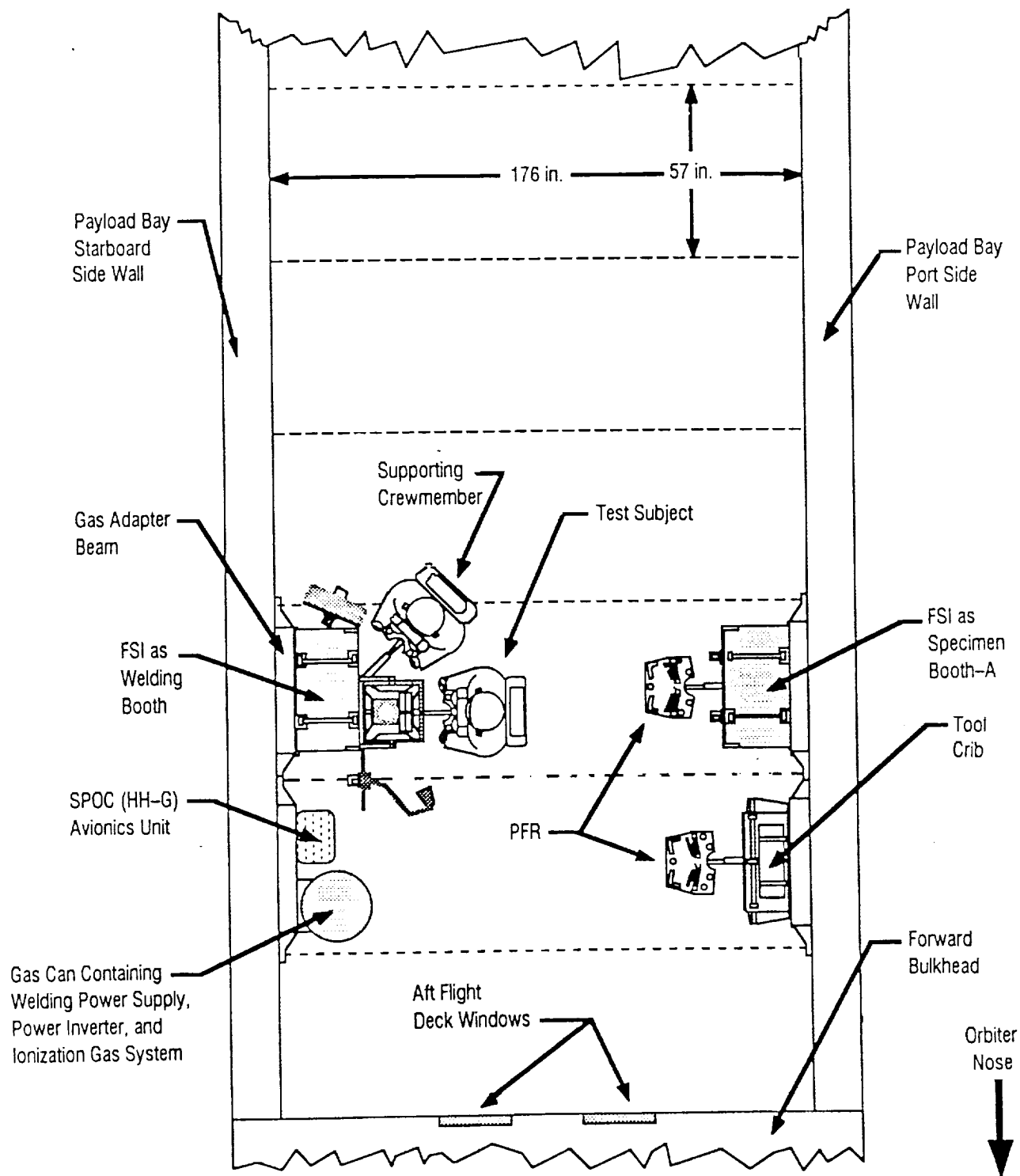


Figure 18. Weld Sample Holding Fixture in 45-Degree Overhead Orientation



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Figure 19. Weld Sample Holding Fixture Pivot-Point Locus



C5155-31

Figure 20. Candidate Arrangement of Work Station Components in Orbiter

welding system and Orbiter interfaces have been obtained. The conventional terrestrially used convective fan cooling system will require substitution by a Freon-114 heat exchanger system, routed through heat-sink blocks and structural brackets of the welding power supply. Furthermore, the heat exchanger must be designed to interface with the Orbiter's Payload Active Cooling Kit (PACK) for added heat rejection. The EVA thermal environment will also require substitution of all components which are incompatible with a minimum storage temperature of -110°C . Proper temperature during operation will be achieved through power dissipation. Informal engineering estimates for these modifications indicated that the cost could be on the order of \$1 million.

Modification of a power supply for operation in a pressurized container would be much simpler. In this case the primary concern is adequate cooling for removal of the waste heat generated by the power supply and the power inverter. Those modifications cited above for cooling would also be required here. However, electrical components would not need to be vacuum compatible. Preliminary, informal engineering estimates for this type of modification indicate that the cost could be on the order of \$250,000.

Additional modifications for support of the ionization gas requirements of the hollow tungsten electrode will be required. Crewmember compatibility will be achieved through compliance with relevant portions of JSC documents SC-M-0003 and SC-M-0002. The potential for unacceptable levels of Electromagnetic Interference (EMI) may require the incorporation of an alternative means of arc initiation such as a touch-start capability. Although normally not favored for aerospace applications, touch starting may be necessary for this experiment. A fully operational welding system might require some other means of arc initiation.

6.4.2 Manual Welding Torch

The design of the manual welding torch will be driven by the features which are required to enable stabilization of the arc in a vacuum, the constraints imposed by operation in the EMU, and safety considerations. The torch shown in Figure 21 depicts a preliminary concept of the incorporation into a conventional torch of the hollow electrode feature required for arc stabilization in vacuum. The torch to be used for the EVA experiment will require further design modifications.

For example, the end of the torch where the hollow tungsten electrode is located will be designed as an interchangeable unit as illustrated in Figures 22 and 23. This will facilitate changing the electrode in the event of degradation or contamination. The dexterity limitations imposed by the pressure suit gloves preclude the conventional method of removing and replacing only the electrode. The interchangeable torch end will also permit ceramic "potting" of the electrode to prevent stray arcing and to minimize electrode exposure.

Another modification to the torch will be the addition of a current control lever to the body of the torch. The standard means by which a welder controls welding current is with a foot pedal. Welding current is proportional to pedal position. In other words, the further the

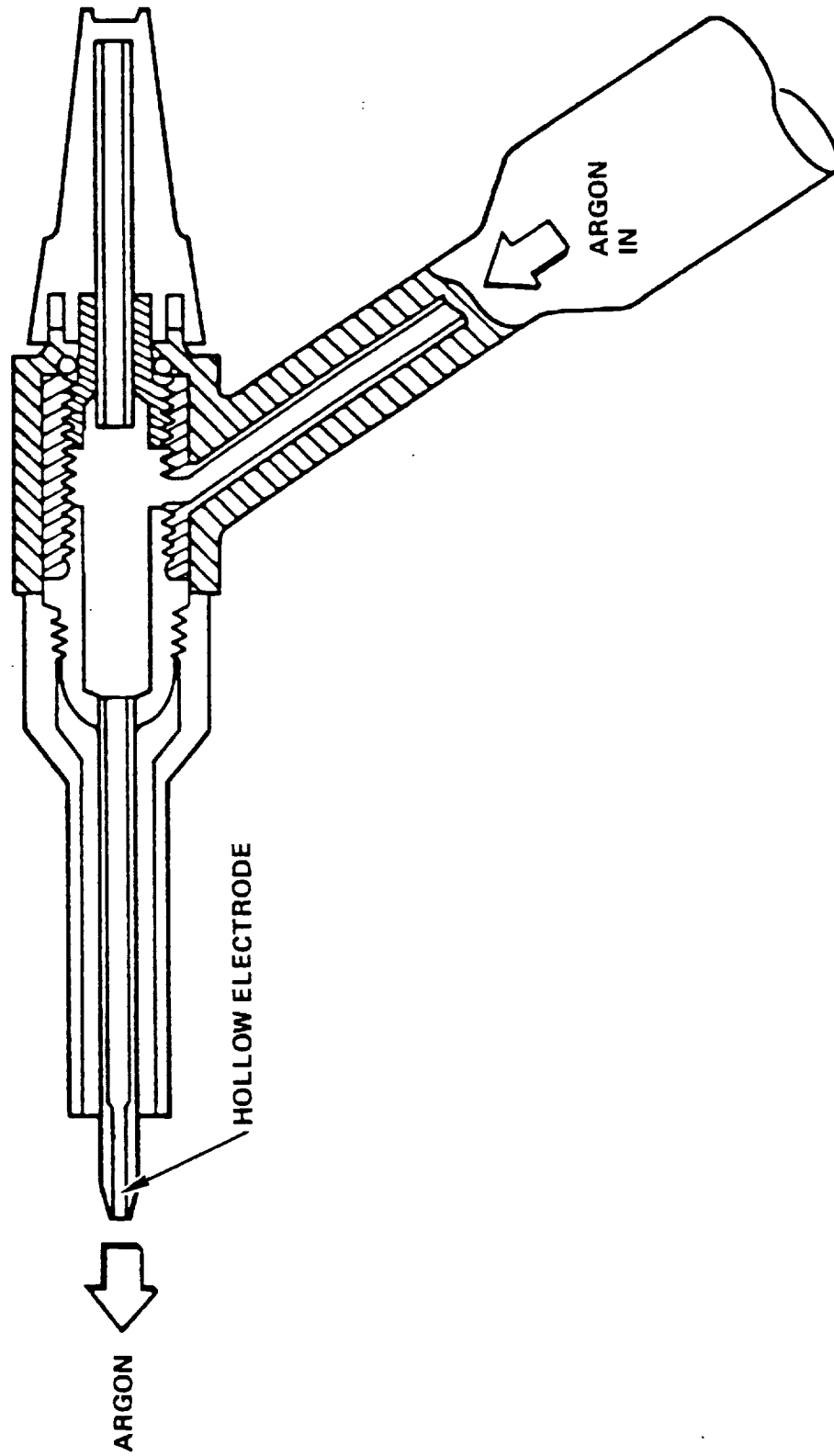


Figure 21. Preliminary Concept of a Conventional Manual Gas Tungsten-Arc Welding Torch Incorporating the Hollow Electrode Concept Required for Arc Stabilization in Vacuum

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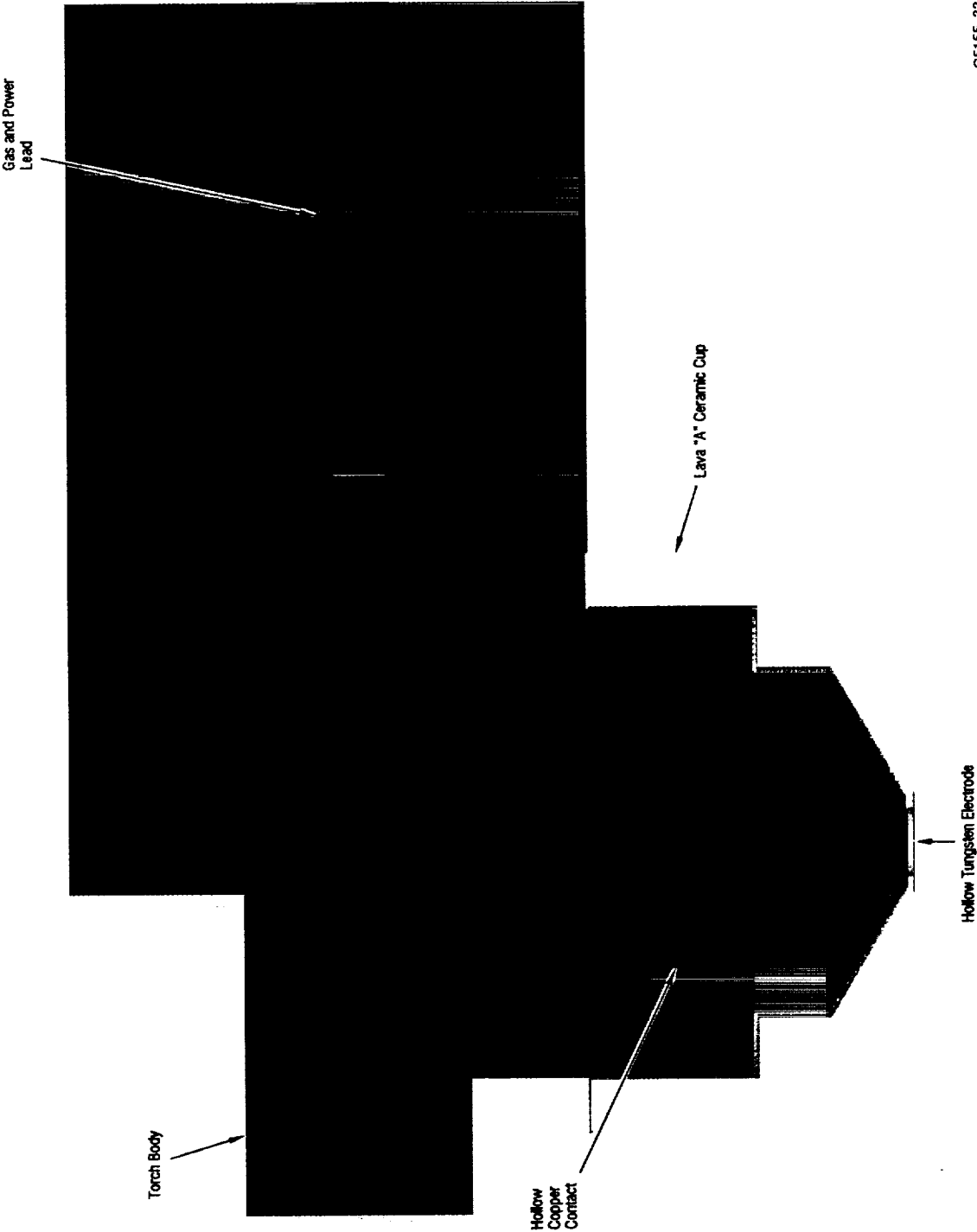
Dimensions are in Millimeters

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Figure 22. Conceptual Design of EVA-Compatible Manual Gas Tungsten-Arc Welding Torch

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Figure 23. Details of Interchangeable Electrode Unit on EVA Gas Tungsten-Arc
Welding Torch

pedal is depressed, the greater the welding current. Clearly, this arrangement would not be suitable for an EVA astronaut in a foot restraint. By replacing the foot pedal with a hand-actuated lever attached to the torch body, the astronaut can retain control of welding current.

The final addition to the torch design will be a detachable heat shield. This shield, which will clamp to the body of the torch, will protect the astronaut's glove from contact with just-welded, hot surfaces.

6.4.3 In-Place Tube Weld Head

Development of the in-place GTAW tube weld head for EVA compatibility will require several modifications. First, the electric drive motor must be changed to a vacuum-compatible model. Next, internal electrical insulation must be added to prevent arcing which could cause internal damage. Modifications to the gas feed system will also be required to support the hollow electrode required for welding arc stabilization. Finally, latching mechanisms and electrode alignment devices must be modified as necessary to enable proper operation by the crewmember wearing pressurized EMU gloves. An example of a typical commercially available in-place tube weld head for terrestrial applications is shown in Figure 24.

6.5 PAYLOAD REQUIREMENTS DEFINITION - TASK 4

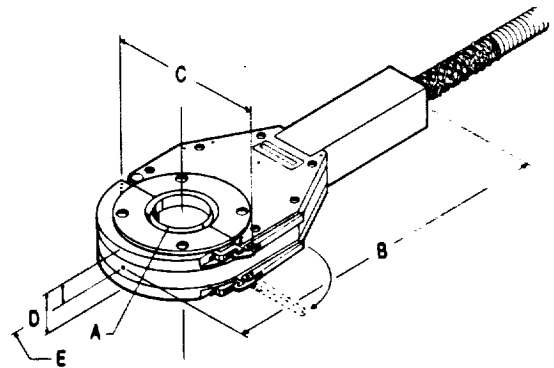
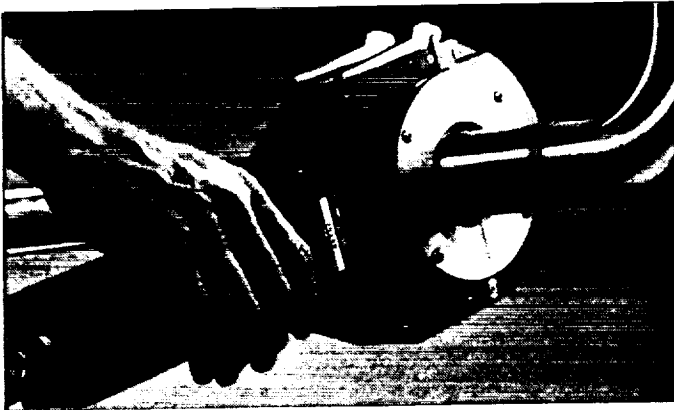
6.5.1 STS Interface Requirements

6.5.1.1 Electrical Requirements. The EVA welding experiment requires Orbiter power for operation of the welding power supply and support systems. The majority of the power is required by the welding power supply. Two STS power allocation categories were considered—primary and secondary payload classes. The primary payload electrical resources would permit the extensive welding options required for the designated tasks of this experiment. Standard secondary payload electrical resources, on the other hand, cannot adequately support the designated experimental tasks.

Orbiter electrical power is distributed to the payload via the Standard Interface Panel during orbital operations at a nominal voltage of 28 Vdc. The continuous maximum power available to a primary payload is 1750 W. Approximately 100 W is budgeted for consumption by the Hitchhiker experiment carrier avionics leaving 1650 W. A limited peak power of 3000 W is available for 15 min at 3 h intervals. Again, 100 W is budgeted for avionics leaving 2900 W of useful power.

The experiment's power system includes a power inverter for dc to ac conversion for operation of the welding power supply. The power inverter used in the G-169 Get-Away Special experiment is a likely candidate for application to the EVA welding experiment. This unit is manufactured by KGS Electronics. KGS Electronics manufactures transistorized airborne static power inverters. Units which operate from 28 Vdc and deliver 240 Vac at 60 Hz are available. An L/C tuned 60 Hz oscillator operating in a class-B push-pull mode is used to generate the 60 Hz signal. This signal is amplified by three stages of class-B push-pull

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Weld Head Specifications (in)

Model No.	A2	B2	D4A	G4A
Tube Diameter	1/8 to 1/2	1/4 to 1 1/4	1/4 to 2 3/8	1/2 to 3 1/2
Maximum Speed (rpm)	10	10	5.0	5.0
Dimensions				
"A" Radius	0.938	1.750	2.250	3.125
"B" Length	9.750	12.625	13.750	15.250
"C" Width	1.875	3.5	5.0	6.875
"D" Thickness	1.250	1.875	2.000	2.000
"E" Tungsten centerline	0.625	0.869	0.869	0.869

- All weld heads utilize d.c. gear motors with d.c. tachometers

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Figure 24. Commercially Available Gas Tungsten-Arc In-Place Welding Head for Terrestrial Applications. Modifications will be Required for EVA Compatibility. (Reproduced with permission of Dimetrics, Inc.)

emitter follower amplifiers. Protective circuits for output overload and thermal runaway are incorporated to make the KGS power inverter unit extremely reliable. The inverter unit can be mounted in any configuration. Since the unit's base plate temperature cannot exceed 74°C, the unit will require active cooling for the EVA welding experiment.

The power conversion efficiency of the KGS power inverter is approximately 85%. A typical value for the efficiency of converting power input to welding-arc power is 80% (a value provided for the ST International power supply which is a candidate for use in the EVA experiment). Thus, the total power conversion efficiency for the experimental hardware is approximately 68%. Applying this efficiency value to the available power, one can determine the approximate current and voltage which will be available for welding as follows:

Continuous Maximum:

Available power for welding system	1650 W
Arc welding power (@ 68% efficiency)	1122 W
Typical arc welding voltage	11 V
Arc welding current	102 A

Limited Peak (up to 15 min/3 h)

Available power for welding system	2900 W
Arc welding power (@ 68% efficiency)	1972 W
Typical arc welding voltage	11 V
Arc welding current	179 A

The corresponding arc welding current values which would be provided by secondary payload accommodations would be 80 A (continuous) and 94 A (peak). This would be marginal at best for the purposes of this experiment.

6.5.1.1 Thermal Requirements. The 68% conversion efficiency of the power inverter/welding power supply combination implies that 32% of the power available to the welding system is lost as waste heat. This means that during continuous operation waste thermal energy must be dissipated at a rate of 528 W (1802 Btu/h). At peak power operation waste thermal energy must be dissipated at a rate of 928 W (3167 Btu/h). Passive cooling of the welding system through radiation, convection, and conduction will probably not be adequate to keep temperatures within acceptable limits. Of the three heat transfer mechanisms, conduction of heat into the thermal mass of the work station would be most effective. However, during an extended experiment the work station structure could become quite hot. The preferred alternative is to utilize the active cooling system available on the Orbiter.

Active cooling of the welding system will be provided by a heat exchanger with a coolant loop system, pressurized to a maximum (NASA requirement) of 200 psia with Freon-114.

The coolant loop will run through heat sink blocks mounted at strategic locations near components such as the main transistors, output rectifiers, and silicon wafers. The coolant loop system extends to the welding torch or in-place tube weld head. This system is interfaced with the Orbiter's Payload Heat Exchanger via the PACK. PACK provides secondary structure, hardware, insulation, and the generic portion of the coolant supply and return lines between the Payload Heat Exchanger Interface and the PACK Interface. The payload's cooling system includes appropriate plumbing to interface with the PACK. In addition, the payload's cooling system provides flow control, pressure control, filtration, and corresponding instrumentation.

6.5.1.3 Structural Requirements. Mounting of the Flight Stowage Items to the Orbiter will be via Get-Away Special Adapter Beams. One candidate configuration for mounting locations is shown in Figure 20.

6.5.1.4 Payload Mass. The estimated approximate payload mass is computed as follows:

Item Mass

3 Flight Stowage Items (3 X 108.2 kg)	325 kg
Attach hardware (3 X 77 kg)	231 kg
Samples	483 kg
Get-Away Special cannister (includes attach hardware)	227 kg
Welding power supply	115 kg
Miscellaneous hardware	<u>45 kg</u>
Total	1426 kg

6.5.2 STS Integration Procedures

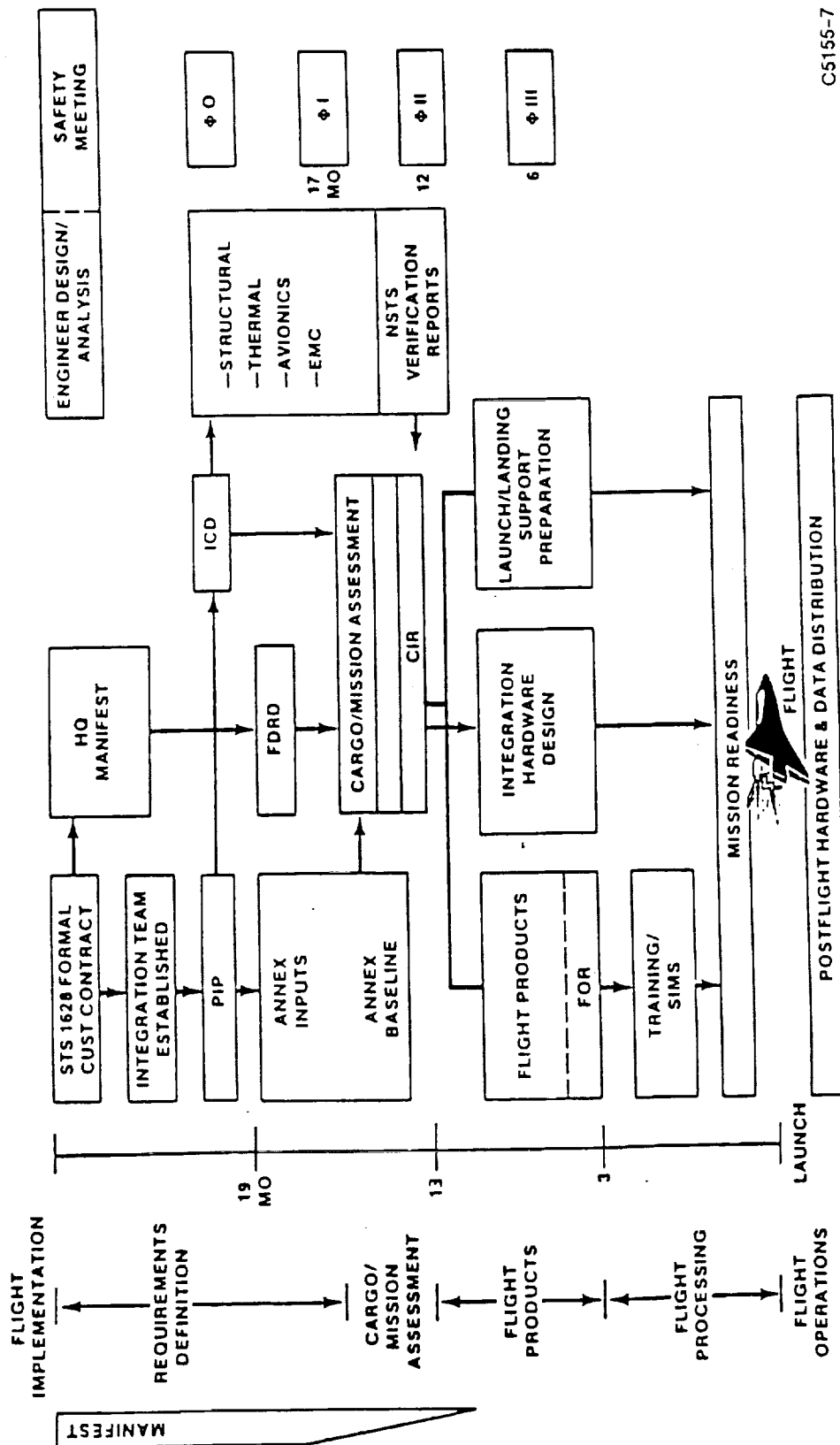
The STS payload integration process involves a complex series of documents and formal reviews involving both NASA and the Customer (in this case Rocketdyne) as shown in Figure 25 [Ref. 11]. The process begins with the submittal of the request for flight assignment, Form 1628. The next major responsibility of the Customer is to support the preparation of the Payload Integration Plan (PIP) and the PIP Annexes. Consultation with the National Space Transportation Systems Office at Johnson Space Center indicated that the relevant annexes for the EVA Welding Experiment are:

1. Payload Data
2. Flight Planning
3. Flight Operations Support
7. Training
8. Launch Site Support Plan



NSTS INTEGRATION AND OPERATIONS

PAYLOAD INTEGRATION PROCESS OVERVIEW



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Figure 25. NSTS Payload Integration Process Overview Showing Critical Activities with a Vertical Time Line

9. Interface Verification

11. Extravehicular Activity

Annex 4 (Command and Data), Annex 5 (Payload Operations Control Center Requirements), and Annex 6 (Crew Compartment Data Requirements) are not expected to be necessary for this experiment. There is no Annex 10.

The Customer supports the development of the payload-to-Orbiter Interface Control Document (ICD) by identifying any unique interface requirements which are nonstandard. Standard interfaces are defined in NASA document ICD A-19001.

The Customer provides the engineering analyses for structural loads, thermal design, and RF compatibility. The Orbiter model and forcing functions are provided by NASA.

In the safety implementation process, shown in Figure 26 [Ref. 12], the Customer is responsible for conducting safety evaluations, preparing hazard reports, and supporting the Phase 0, 1, 2, and 3 Safety Reviews by preparing Safety Data Packages. The Customer must ensure compliance with all requirements of NHB 1700.7 and KHB 1700.7 and implementation of these requirements in accordance with JSC 13830A.

The EVA mission integration process involves some overlap with the other aspects of the payload integration process as well as some independent concurrent activity, as seen in Figure 27 [Ref. 13]. It is anticipated that the nature of the EVA Welding Experiment will require close cooperation between Rocketdyne and NASA throughout this process.

6.6 HUMAN FACTORS EVALUATIONS - TASK 5

6.6.1 Astronaut Office Reviews

Two meetings were held with representatives of the NASA-JSC Astronaut Office to discuss various aspects of the planned spaceflight experiment. The first meeting, with Lt. Colonel Jerry L. Ross, occurred on April 19, 1989. Lt. Colonel Ross is a representative on the Astronaut Science Support Group and is responsible for EVA and space construction. A preliminary compilation of proposed flight task procedures was provided in advance of the meeting for Lt. Colonel Ross' review. Lt. Colonel Ross' comments included:

1. Development of welding technology for space applications is necessary.
2. The objectives of the proposed flight experiment are sound.
3. The organization and structure of the experiment are reasonable.
4. Both crewmembers in the EVA should participate in the welding to provide two data points.
5. He would be willing to try a two-handed task (holding the welding torch with one hand and a wire feeder with the other hand).

SAFETY IMPLEMENTATION

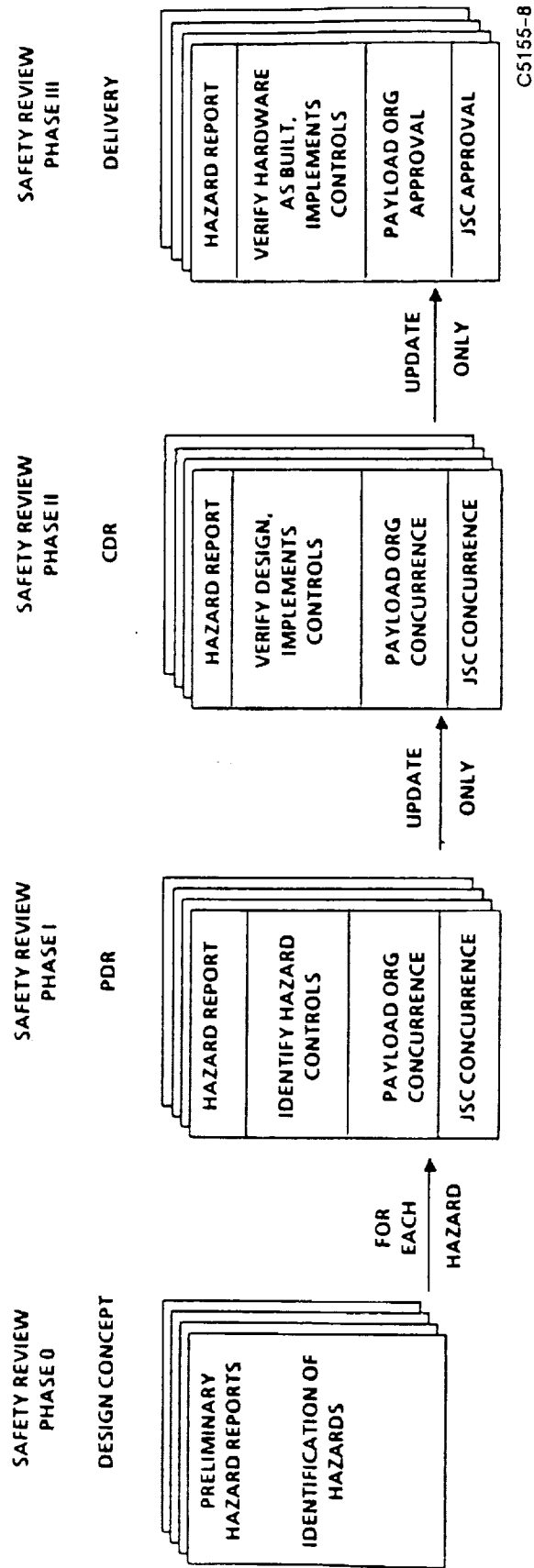
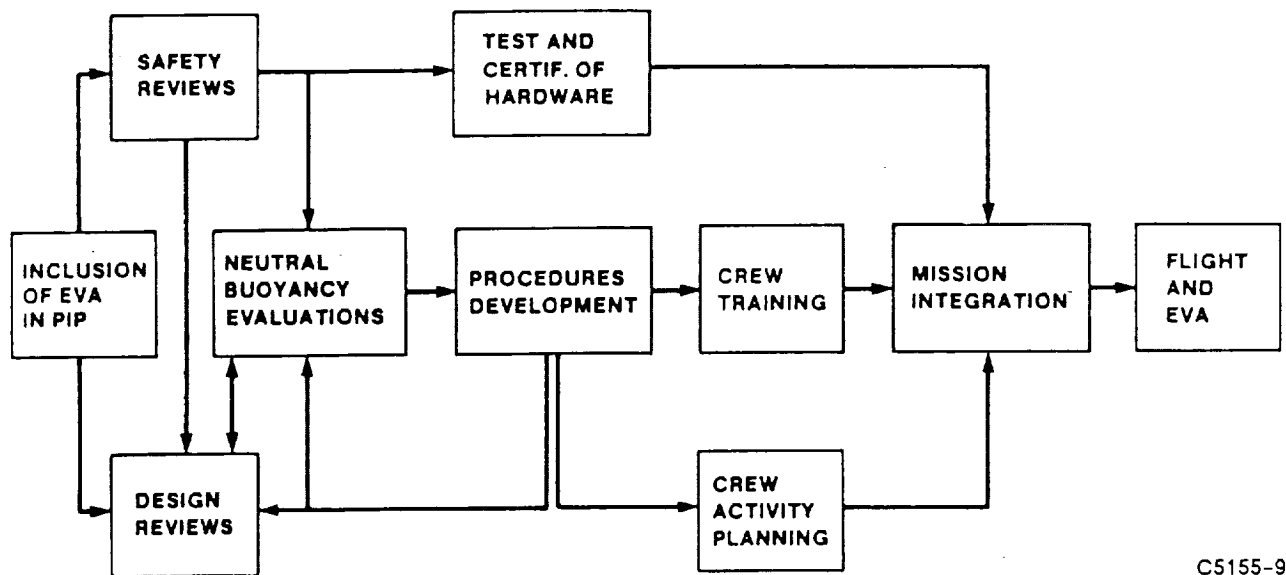


Figure 26. NSTS Safety Implementation Process Showing Key Concerns for Each Safety Review Phase



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Figure 27. Extravehicular Activity Mission Integration Process

6. Foot restraints plus a safety tether will be sufficient. Additional waist tethers for restraint are not necessary.
7. He would be willing to participate in the NASA-TLX workload measurement procedure during the course of the flight experiment.
8. The sample holding frame concept is sound.
9. Mounting the work station on the side wall of the orbiter payload bay would be preferred.
10. Filler metal supplies should be color-coded to prevent confusion.

The second meeting took place at the California Polytechnic State University between Cal Poly personnel working on the project and Commander Robert "Hoot" Gibson of the NASA-JSC Astronaut Office. At the time of the meeting the Cal Poly personnel were preparing work station mock-ups with which to perform the flight experiment time line simulation test. Various aspects of the work station arrangement, including crew translation requirements, and EVA operations in general were discussed. Commander Gibson's comments and suggestions, as well as those of Lt. Colonel Ross, have been given full consideration in the subsequent development of this experiment.

6.6.2 Safety Evaluation

As discussed above, the formal process of assuring that a Shuttle payload meets all applicable safety requirements is well defined and rigorous. Although it was felt that such formalism was not necessary in the current project, it was appropriate, and essential, that thorough consideration be given to safety issues arising from the unique aspects of the proposed experiment. To this end, a comprehensive list of issues was developed along with approaches for addressing each. The first ten of the fourteen issues relate to maintaining the integrity of the EMU. It must be guaranteed that the pressure suit will not be burned, punctured, or cut. This list appears as Table 2. A preliminary copy of the list was reviewed by, and discussed with, Matt Cole and Richard Serpas of the NASA-JSC Safety Division. No prohibitive issues have been identified. Therefore, it can be concluded that the EVA welding experiment can go forward and that the safety of the crew and the vehicle will not be jeopardized.

6.6.3 High Temperature Containerless Aircraft Furnace (HiTCAF) KC-135 Tests

A series of welding tests was conducted on board the NASA KC-135 research aircraft during low-gravity periods produced through flying parabolic trajectories. The hardware used in these tests was a modified GTAW power supply known as the High Temperature Containerless Aircraft Furnace (HiTCAF). At the writing of this report, four flight periods have been supported, with each period involving up to four flights. Support of six flight periods

Table 2. EVA Welding Experiment Safety Issues
(Sheet 1 of 2)

Issue	Required Analysis	Approaches
1. Sharp electrode point	None	a. Use minimal stick-out b. Use protective shroud c. Use 180° (blunt) point
2. Hot electrode	None	a. Use minimal stick-out b. Maximize active cooling of torch c. Use protective shroud
3. Hot plate samples	None	a. Uncover only sample being welded b. Apply heat sensitive tape in strategic areas c. Sample being welded will be recessed in holding frame
4. Hot tube samples	None	a. Wrap with thermal blanket b. Use case-type cover c. Apply heat-sensitive tape in strategic areas
5. Metal expulsion from back of plate	a. Experimentally evaluate conditions for expulsion	a. Back surface contained by sample holding frame
6. Metal expulsion from face of plate	a. Experimentally evaluate conditions for expulsion b. Look at existing data on solidification and cooling rates	a. Use brush or catcher b. Stop experiment if observed
7. Metal expulsion from root of tubes	None	a. Cap ends to provide containment
8. Metal expulsion from face of tubes	a. Same as 6.	a. Same as 6.
9. Hot or sharp filler wire end		a. Automatic retract within shroud
10. Sharp edges on weld beads	a. Unlikely occurrence	a. Thermal protection covers will provide adequate protection

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**Table 2. EVA Welding Experiment Safety Issues
(Sheet 2 of 2)**

Issue	Required Analysis	Approaches
11. Loss of control of arc position	None	<ul style="list-style-type: none"> a. Crew releases current control to stop current and extinguish arc b. Withdraw torch from work to extinguish arc
12. Electrical shock	None	<ul style="list-style-type: none"> a. Ground circuit will be isolated from workstation b. Specimen being welded is path of least resistance c. Only exposure of "hot" circuit will be electrode tip
13. UV radiation	None	<ul style="list-style-type: none"> a. Adequate attenuation by EMU visor b. Use supplementary dark shields c. Use low reflectance surfaces at workstation
14. IR/radiant heading of EMU	<ul style="list-style-type: none"> a. Perform vacuum chamber test thermo-coupled suit samples at various distances from the arc 	<ul style="list-style-type: none"> a. Physical shielding b. Supplemental thermal protection garment

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was planned. However, because of the manifesting of the payload fewer flights than expected have been supported to date.

Through these tests the feasibility of performing in-place tube welding operations in low-gravity was demonstrated. In addition, a series of tests of manual welding in low-gravity was performed. This significant event marked the first time that American researchers have attempted to perform manual welding tasks in low-gravity and the first attempt by researchers of any nationality to perform manual arc welding tests in low gravity. Figure 28 shows a welding test underway in a glove box constructed especially for this work. Preliminary results from these tests indicate that the efforts were quite successful and that no difficulties in welding were associated with the low-gravity environment.

The weld pool was observed to be "well behaved" with no tendency for metal expulsion or spatter. These tests also provided an opportunity to exercise the NASA-TLX subjective workload measurement system in conjunction with the performance of welding tasks in an operational low-gravity environment. Additional data will be accumulated by continued effort through a no-cost extension of the current contract. Results of this work will be reported in a supplement to this final report.

6.6.4 Timeline Simulation Test

In the planning of an EVA space flight experiment a critical piece of information is the total amount of time required to perform all of the necessary tasks. Clearly, the EVA Welding Experiment being planned in this project is a complex experiment that will require a substantial amount of EVA time. Following consultation with Lt. Colonel Jerry Ross of the NASA-JSC Astronaut Office, it was determined that the best means of developing an estimate of the required EVA time was to conduct a time study during a manned laboratory simulation of the flight experiment. Of course, such a simulation is performed in 1-g conditions and the test subjects do not suffer the constraints of working in pressure suits. Nevertheless, such a simulation can yield a reasonable timeline estimate.

Subcontractor personnel at Cal Poly were requested to construct mock-ups of the conceptual work station and to perform a simulation of the flight experiment. Photographs of the mock-up FSIs were shown previously in Figures 12 through 14. In Figures 29 through 34 the Cal Poly personnel are shown working through the flight experiment simulation. Figure 29 shows the relative orientations of the test subject and the supporting crewmember in foot restraints at the welding site. Figure 30 illustrates the test subject welding in the 45-deg overhead position. Figure 31 shows the test subject welding in the 45-deg chest-level position. Figures 32 through 34 show various aspects of the in-place tube welding operation to be performed in Task 12.

The total estimated time for the flight experiment derived from this simulation is approximately 4 h. A summary of the times recorded during the simulation is provided in Appendix 5.



Figure 28. First-Ever American Low-Gravity Manual Welding Tests Being Performed on the KC-135 by Rocketdyne Engineers Using Elements of the NASA-MSFC High Temperature Containerless Aircraft Furnace (HiTCAF)

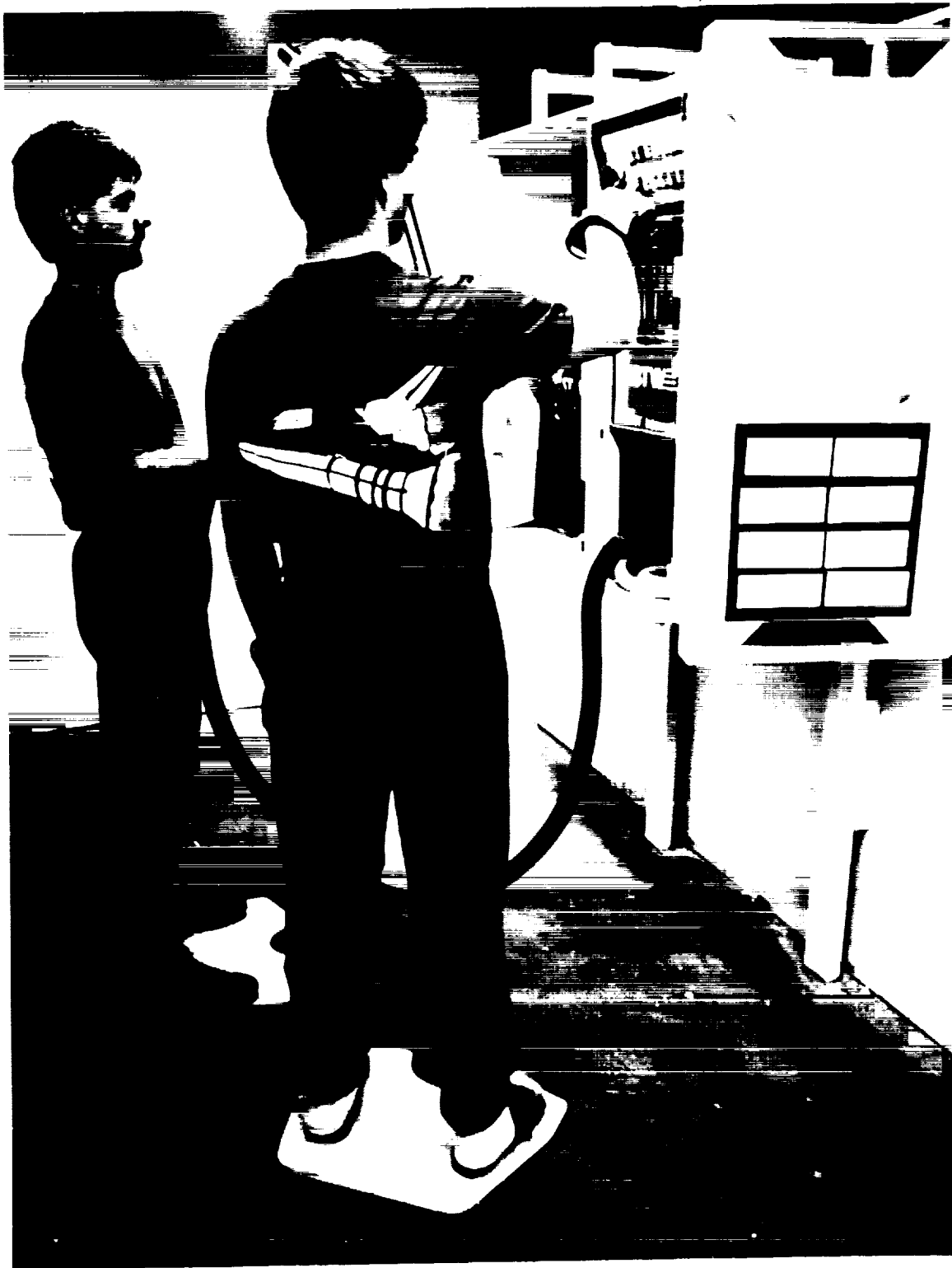


Figure 29. Relative Orientations of the "Test Subject Crewmember" (Left) and the "Supporting Crewmember" (Right) in Foot Restraints at the Welding Station During Time Line Simulation



Figure 30. "Test Subject Crewmember" Welding in the 45-Degree Overhead Orientation During the Time Line Simulation of Task 4

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Figure 31. "Test Subject Crewmember" Welding
in the 45-Degree Chest-Level Orientation
During the Time Line Simulation of Task 5

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Figure 32. "Test Subject Crewmember" Attaching Tube Weld Head to Specimen During Time Line Simulation of Task 12. "Supporting Crewmember" is Operating Power Supply Controls.

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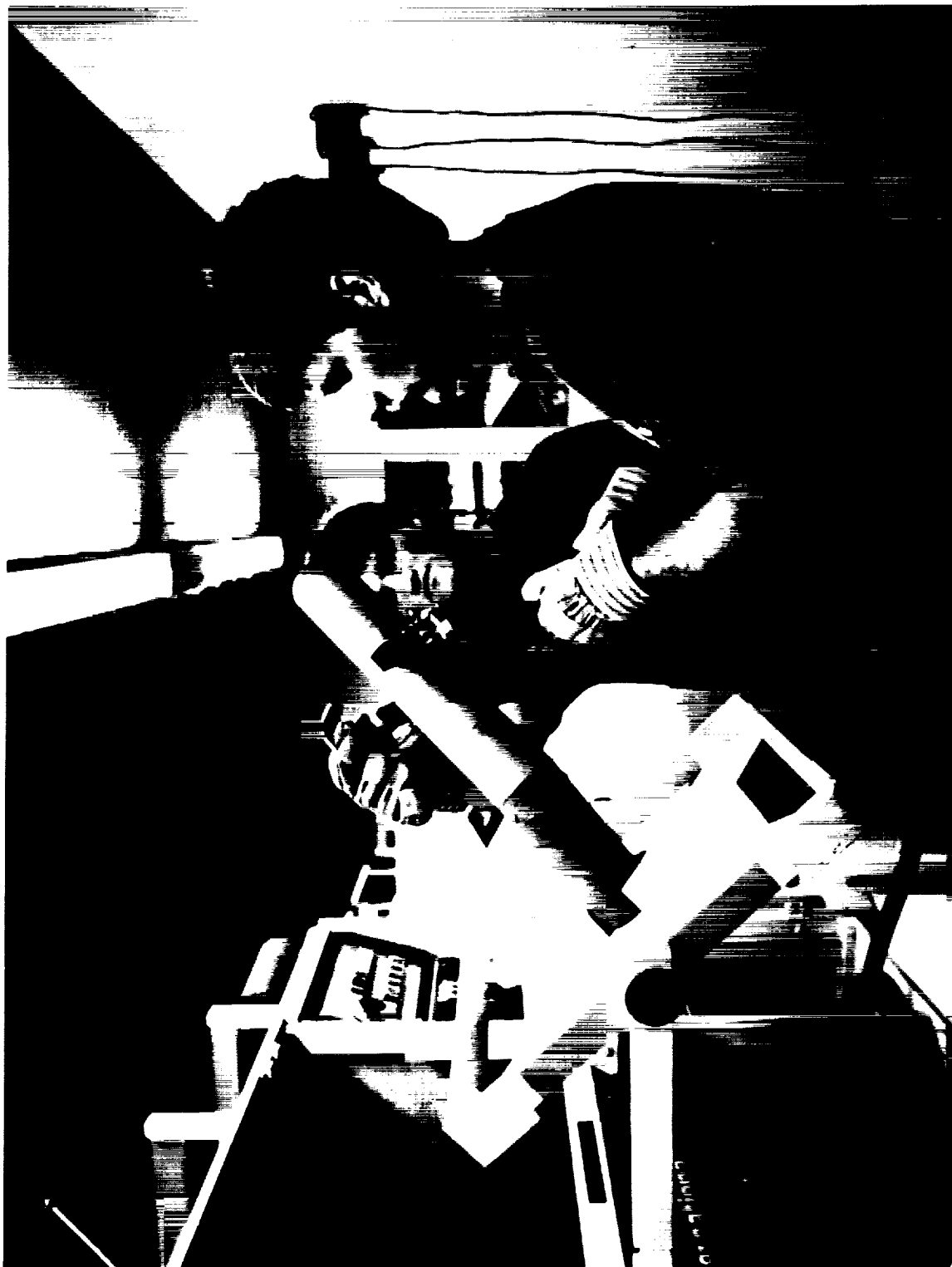


Figure 33. Supporting Crewmember Assisting "Test Subject Crewmember"
During Time Line Simulation of task 12

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Figure 34. "Test Subject Crewmember" Positions Tube Weld
Head with Specimen in Another Orientation During
Time Line Simulation of Task 12

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When referring to the data in Appendix 5 it will be noted that the task sequence is somewhat different than that presented in Figure 6 and in Table 1. This is because a preliminary task sequence version was used in the simulation. However, when the tasks are rearranged in the present sequence the total elapsed times for the sequence and the simulation are nearly identical. Some variance from the notation used elsewhere in this report will be noted in the simulation data, as well.

As the flight date draws closer and NASA flight planners become involved, further evolution of the experiment task sequence is anticipated. The data developed in the current simulation should serve as a good basis for making initial timeline estimates as this evolution progresses.

6.6.5 Crew Interaction

Design of the welding site orientation relative to the crewmembers and of the orientation of the crewmembers relative to each other is of primary importance because work envelopes, reach, and safety are critical in an EVA operation. There are three basic functions that the crewmembers must perform. These are: serve as test subject, control the welding system, and retrieve and stow samples. These responsibilities can be divided in either of two ways. First, one crewmember can serve as both test subject and system controller while the other crewmember only transports samples. Second, one crewmember concentrates on acting as the test subject while the other manages the system and transports the samples. Three concepts for orienting the crewmembers at the work site have been developed. These concepts, outlined below, are presented in decreasing order of preference.

1. This concept, shown in Figure 35 is most preferred. In this scenario one crewmember's sole function is that of test subject. Since safety is of primary consideration, and the point of greatest concern is the welding torch, this concept allows the test subject to devote full attention to control of the torch at all times. All other functions must be handled by the supporting crewmember. The crewmember orientations optimize accessibility of the test subject to the sample holding fixture and accessibility of the supporting crewmember to both the fixture and the system controls while enabling him to visually monitor the activities of the test subject. Furthermore, direct visual contact with the experiment from the aft flight deck windows and the forward bulkhead cameras is possible due to the orientation of the test subject.
2. The second concept delegates responsibilities in the same fashion as the first concept. However, in this case the two crewmembers are placed opposite each other with the test subject facing aft and the supporting crewmember oriented at 45 deg relative to the longitudinal axis of the Orbiter as shown in Figure 36. This concept provides the supporting crewmember with a greater working envelope since the test subject is no longer adjacent to him. However, the test subject's left arm is constrained because of the volume of the EMU and the proximity to the door of the FSI. Direct visual contact with the experiment from the aft flight deck windows and forward bulkhead cameras is impeded by the test subject's position.

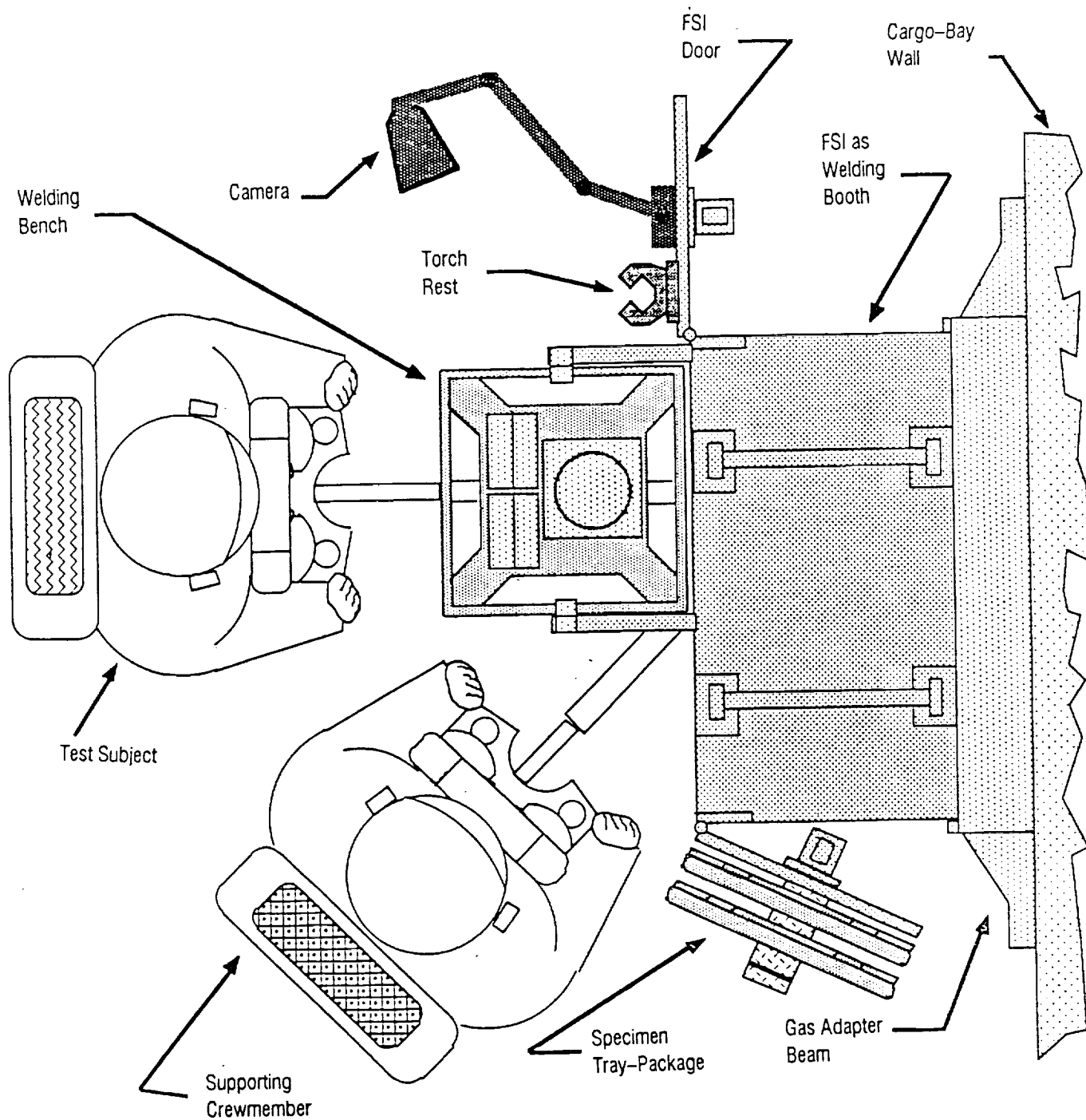
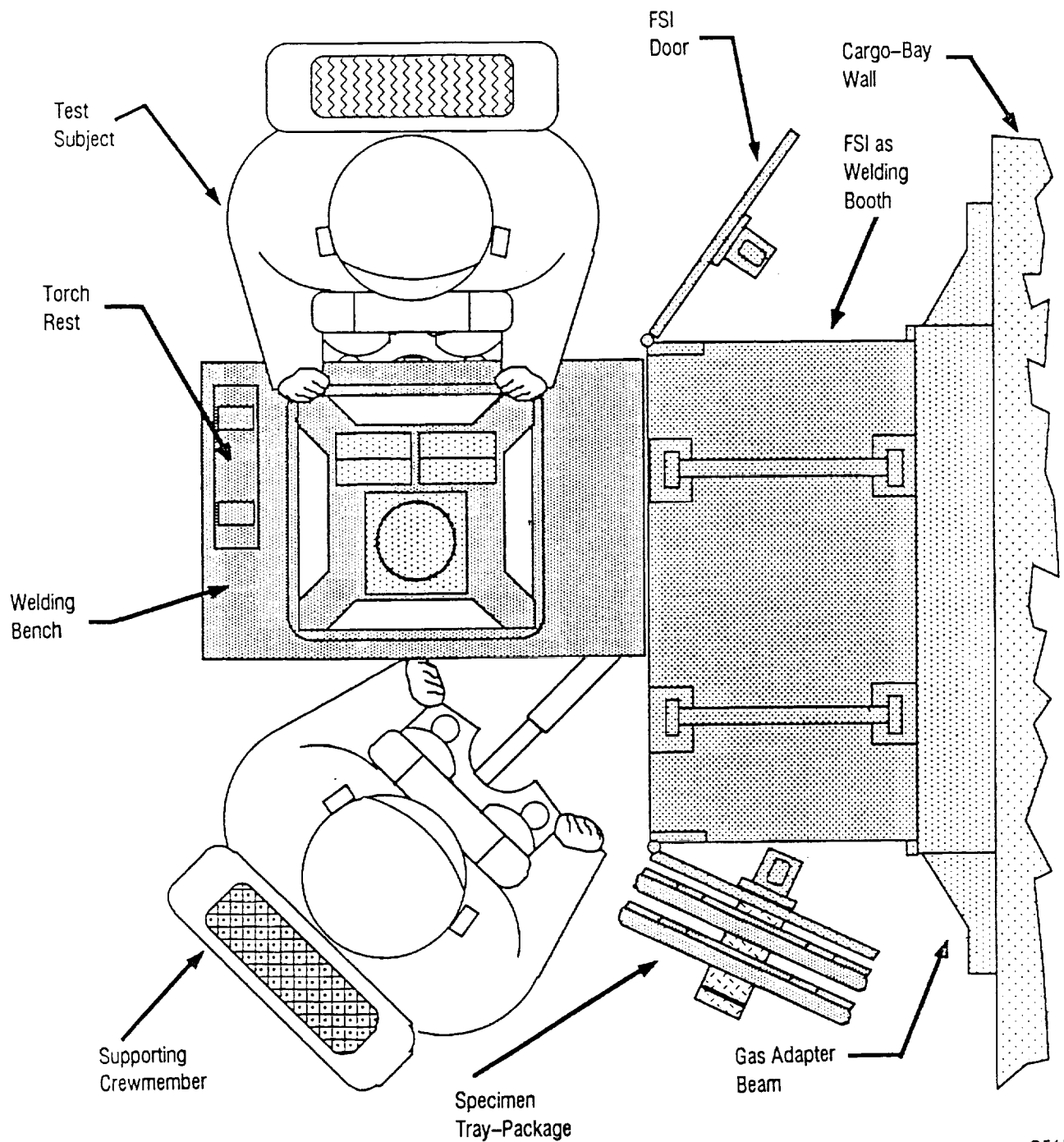


Figure 35. Preferred mode of crewmember interaction in which test subject is responsible only for performing welding tasks. Supporting crewmember controls system and manages samples.



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Figure 36. Less desirable mode of crewmember interaction. Crewmember responsibilities are the same as in Figure 35, but the position of the test subject blocks the view of the work site from the aft flight deck.

3. The third concept requires that the test subject also serve as system controller. The only function of the supporting crewmember is to retrieve and stow samples. This allows simultaneous execution of welding and specimen retrieval resulting in more efficient use of time. However, this concept sacrifices the safety of the test subject by increasing his workload and allowing absence of the supporting crewmember. A third possible arrangement of crewmember positions is shown in Figure 37. In this arrangement the test subject is in a disadvantageous position as discussed above and movement by the supporting crewmember may also be constrained.

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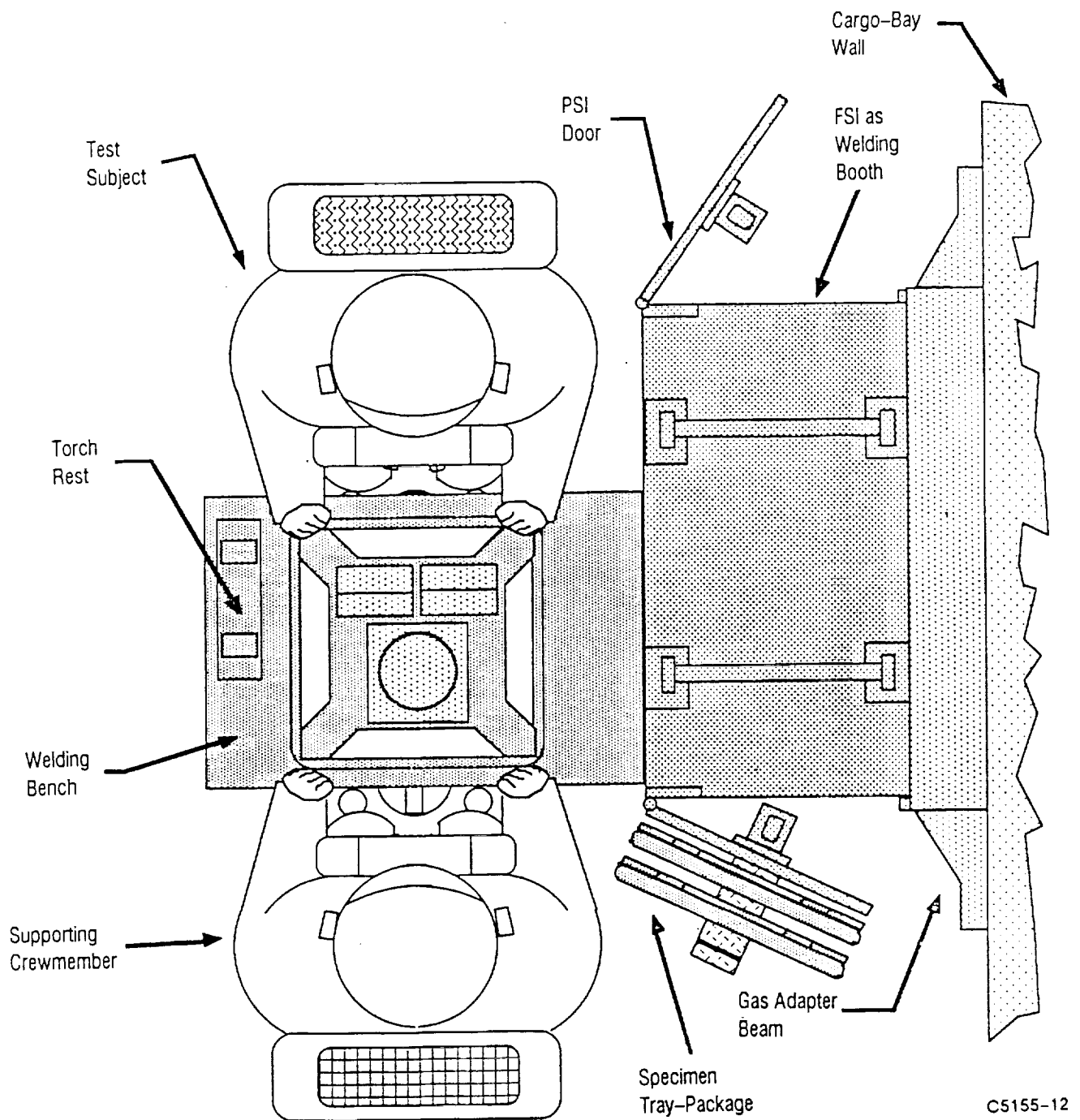


Figure 37. Least desirable mode of crewmember interaction. Only responsibility of supporting crewmember is sample management. Test subject experiences higher workload and blocks view of worksite from the aft flight deck.

7.0 ROCKETDYNE-FUNDED WORK

7.1 IR&D VACUUM GTAW PROCESS CHARACTERIZATION

Rocketdyne is continuing internally funded development of the hollow-electrode GTAW process for use in space. Tests are currently planned to take place at both the Marshall Space Flight Center and at the NASA Lewis Research Center Microgravity Materials Science Laboratory. Experimental equipment available at these two facilities will permit more in-depth characterization of the process and verification of expected operation at vacuum levels currently unattainable in Rocketdyne's laboratory facilities.

7.2 UNDERWATER TEST FACILITY TUBE WELDING TIME STUDY

A test is being planned to take place in an underwater simulated EVA environment. The objective of this test will be to develop detailed time-study data for the manual operations associated with the use of an in-place tube welding device by a test subject in a pressure suit in a simulated low-gravity environment. This data will be used in a comparative study of the relative benefits of mechanical couplings versus welded connections for on-orbit assembly of space structure utility lines. Figures 38 and 39 [Ref. 14] show a test subject during previous tests of mechanical coupling operations conducted by the McDonnell Douglas Astronautics Company. The anticipated test date is September 1989.

7.3 VISIT TO SOVIET SPACE WELDING TECHNOLOGY DEVELOPMENT SITES

In June 1989 representatives from three American aerospace firms and the American Welding Society traveled to the Soviet Union for in-depth discussions of the Soviet development of space welding technology. The group began the tour with a visit to the Paton Welding Institute in Kiev, where the URI electron beam device was developed. There they were treated to demonstrations of the gun operating in a man-rated vacuum chamber. The group then travelled to the Cosmonaut Training Center near Moscow. Cosmonaut Major General Vladimir Djanibekov, who had participated in the 1984 EVA welding experiment, served as the group's escort. Figure 40 shows Hal Conaway, Rocketdyne's representative, discussing the multi-purpose electron beam device with Major General Djanibekov. Preliminary discussions were conducted on the subject of U.S. organizations obtaining rights to the electron beam gun. The results of these discussions were encouraging.



Figure 38. Underwater EVA simulation of assembly of utility lines with mechanical couplings. This work site configuration is similar to that to be used for planned underwater EVA simulation of utility line assembly with in-place welding technology.

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Figure 39. Front View of Test Subject During Underwater EVA Assembly Simulation

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Figure 40. Rocketdyne representative Hal Conaway discusses Soviet multi-purpose electron-beam device with cosmonaut Major General Vladimir Djanibekov.
Major General Djanibekov worked with this device during the EVA Welding Experiment performed in July 1984.

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8.0 ESTIMATED COST AND SCHEDULE FOR COMPLETION

8.1 COST

The ROM estimate for the 32-month program required to complete the flight experiment and postflight analysis is \$2.5 million which covers approximately 10 man-years of effort, power supply with related packaging hardware, development material and travel. This estimate is for budgetary and planning purposes only and does not constitute a firm commitment on the part of Rockwell International Corporation.

8.2 SCHEDULE

The schedule shown below includes only the major activities required to carry this experiment to completion. Under each item there will be additional subtasks not shown here. For example, for each item of hardware design, fabrication, and qualification testing will be required.

Task	Months from Start							
	4	8	12	16	20	24	28	32
Hardware Development								
Work Station								
Power Supply								
Manual Torch								
Wire Feeder								
In-Place Weld Head								
Sample Frames								
Samples								
Crew Training								
Baseline Data Development								
Safety Review	[0]	[1]	[2]		[3]			
STS Integration								
Flight								
Postflight Analysis								

D561-0001

9.0 CONCLUSIONS AND RECOMMENDATIONS

1. A spaceflight experiment has been defined which will provide the data necessary to evaluate the ability of astronauts to perform welding operations in EVA.
2. The successful performance of this flight experiment will provide the data necessary to complete the development of a fully functional, highly flexible on-orbit welding capability for repair and assembly.
3. Preparations for the flight experiment could be completed within 24 months of contract initiation. An additional 8 months following flight would be required for analysis of the results.
4. The ROM estimate of this 32-month program is \$2.5 million. It is estimated that approximately \$450,000 in GFE will be required in addition.
5. There are no prohibitive safety issues associated with this experiment.
6. Experiments performed on board the KC-135 research aircraft have demonstrated the feasibility of both manual GTAW and automated in-place gas tungsten arc tube welding in low-gravity.
7. Laboratory simulation of the flight experiment tasks has shown that approximately 4 h of EVA time will be required.

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APPENDIX 1

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A1-1

APPENDIX 1

CURRENT SITUATION

Selection of a welding process for EVA applications is a complex, but not an unprecedented undertaking. The Soviets and NASA have each been involved in efforts employing electron beam technology [Ref. 15, 16]. Little appears to have been done in the U.S. after a hand held torch was developed by Hamilton Standard in 1967. The Soviets have tested a similar device "in-vivo", and displayed a mock-up of their EVA electron beam welding system at the American Welding Society Convention in New Orleans, LA. during April of 1988. Arc and plasma fusion methods have historically been shunned because they require large volumes of shielding, and arc sustaining gas. Laser processes for space joining applications have been examined recently [Ref. 17].

A recent technological breakthrough at Rocketdyne has circumvented the major objections to arc welding in space. Sustainable, high-energy arc welding has been accomplished in vacuum using a novel hollow-tungsten, ultra-low gas flow GTAW process. Welds on a variety of materials in a variety of thicknesses have been made using this process [Ref. 18]. This process behaves as an exciting hybrid of the arc and plasma processes.

CRITERIA FOR PROCESS SELECTION

Selection of a welding process for the space environment involves the following considerations:

- Process efficiency, in terms of total energy required to produce a particular beam or arc energy and in terms of the efficiency of arc or beam transfer to the work. Equipment efficiency in terms of net deliverable energy per kilogram of equipment is critical for payload management.
- Adaptability of the process to a spectrum of work geometries and an assortment of base materials, to include ease of process control
- Impact of the process on operator and mission safety
- Process equipment reliability.

DISCUSSION OF PROCESSES

Four processes were considered for space applications, the classic arc/plasma process, the laser process, the electron beam process, and the novel hollow-tungsten process pioneered by Rocketdyne. Interestingly, a Soviet researcher briefly discussed hollow-tungsten GTAW vacuum applications in 1973 [Ref. 19], but no further references to the process were found in the literature. The basic arguments against standard arc fusion processes, a lack of vacuum stability and the copious amounts of gas required, are still valid. Thus, of arc processes, only the novel Rocketdyne approach is considered in the following comparison. In this discussion

Energy Efficiency

Energy efficiency is critical. Waste heat must be managed, available power sources cannot be overtaxed, and lift weight and volume cannot be compromised. Any process designed to weld materials must deliver power densities between 1 and 10,000 kW/cm² to the surface of a material. Lower values cannot produce melting, higher values produce only explosive vaporization. Laser and electron beam processes are often lumped together as "high energy density" processes. This is unfortunate because the nature of the beam-material interaction and the nature of the beam generation process for the two are quite different. Many references quote high efficiencies for electron beam processes [Ref. 20-22]. However, in high-efficiency operation, the beam-material interaction is in the keyhole mode, as opposed to the conduction mode. In keyhole operation, the energy from the beam is sufficient to vaporize a path through the baseplate so that the beam energy can be delivered through thickness immediately, rather than it being delivered to the internal regions by conduction from a surface spot. The vapor pressure generated in the cavity is sufficient to keep the hole from collapsing through the action of surface tension or hydrostatic forces, the latter of course would be obviated in space.

Several researchers have noted that the laser process "keyholes" at lower traverse velocities in vacuum conditions. Similar behavior has been noted for electron beam processes, but was attributed to attenuation of the electron beam by any atmosphere present. Several theories have been advanced to explain the phenomenon in lasers. The most popular propose that under reduced pressure the keyhole stability is extended to lower power densities and reduced travel speeds by an increase volatility of work material. The process easily generates the overpressure required to maintain the keyhole at lower effective pool temperatures [Ref. 23]. Furthermore, at reduced pressures, the plasma plume that interferes with coupling has a shorter residence time in the pool vicinity [Ref. 24]. It is not unreasonable to expect that both mechanisms function. Some compromise in bead quality, caused by material expulsion was noted in these tests.

In the initial stages of laser joining much energy is lost by reflection, posing a danger to the operator and nearby structure. Low power beams will have severe problems in the initial stages of welding if the surface has not been preheated by the sun.

To deliver 1 to 2 kW of useful power to the workpiece, laser candidate systems would require a minimum available power of 5 to 10 kW [Ref. 25]. This would require heat management of a minimum of 60 to 120 kcal of waste heat per operation minute. Estimates of the efficiency of energy transfer for electron beam and gas tungsten arc welding processes abound [Ref. 20-22, Ref. 26-28]. The estimates for electron beam efficiency vary as a function of welding mode, from 60% in conduction mode to 75% in keyhole mode. Arc process estimates range from 50% to 75% overall. This involves a 90% conversion at the power supply and an 80% conversion at the arc [Ref. 29, 30]. Electron beam and hollow tungsten

processes, for the same deliverable power require 1.2 to 2.4 kW sources. These processes generate on the order of 6 kcal of waste heat per operation minute.

Efficiency considerations will drastically limit the use of high power lasers in space. Hollow tungsten and electron beam processes are each competitive from this standpoint.

Adaptability

The problem of adaptability can be related to efficiency. Laser systems, for example, have an initial coupling efficiency that is a function of lasing medium and target spectral absorption. For metals this initial coupling efficiency varies between 10% and 30%. The majority of metals have no characteristic color and reflect most incident light. In the IR regions delivered by NdYAG and carbon dioxide lasers suitable for welding, steels and aluminum target materials absorb less than 10% incident light [Ref. 31]. After initial heating the coupling improves to over 40% for conduction limited welds [Ref. 32] and over 90% for keyhole operation [Ref. 33].

Plug to beam efficiency for these lasers varies between 5% and 20% for the carbon dioxide laser and 0.1% to 5% for the NdYAG lasing medium [Ref. 25]. This plug to beam efficiency is a severe drawback for carbon dioxide based systems. It is also a severe problem for NdYAG lasers, but several investigators have suggested solar pumping as a primary energy source [Ref. 17]. Solar pumping would require large collecting mirrors and complex operating schedules. Laser proponents often cite the specific energy input, the heat delivered to the work that produces melting divided by the total power delivered to the work as a argument in favor of laser joining [Ref. 34]. The high melting efficiency indicates that little "waste heat" is delivered to the work, minimizing the heat affected zone. For space applications concentrating process inefficiency in power supply conversions presents no real advantage, the waste heat must be managed. Further, this normalizing effect only occurs in keyhole operation, in conduction mode there is no advantage over the arc process.

Variation in target thermal diffusivity can also limit versatility. Higher power and shorter pulse times are superior for Al applications because of its high thermal diffusivity. Conversely, stainless steels require low power and long pulse duration particularly in the conduction mode [Ref. 34]. Heat sink variation, based simply on thickness can also effect process efficiency, the beam interaction time for Al alloys varies from 0.05 ms at a thickness of 0.125 mm to 19 ms at a thickness of 2.5 mm. Over the same range in stainless steels the interaction time varies from 1 ms to 400 ms. Banas [Ref. 34] has pointed out that keyhole operation of beam processes requires travel speeds on the order of 10-1000 mm/s. Eagar has shown that the implied operator response time, tens of microseconds to hundredths of seconds, relegates the operation of these processes to automated systems [Ref 35]. This is particularly true for thin materials that might be encountered in EVA applications.

Beam processes imply a concern over focal point location, and depth of focus. Laser processes are hampered by a restricted depth of focus, and severe limitations for manual op-

Beam processes imply a concern over focal point location, and depth of focus. Laser processes are hampered by a restricted depth of focus, and severe limitations for manual operation results. A change in the working distance of 1mm will render a keyhole process unstable. Electron beams have an extensive depth of focus and are less susceptible to variations in the working distance.

Beam processes require excellent control over joint preparation and fit-up. Many repair situations would be unmanageable for these processes. The hollow tungsten process is more tolerant than the terrestrial gas tungsten arc process, and would be adaptable to poor fit up and repair situations.

Existing electron beam welding guns are bulky because they contain radiation shielding, source cooling and accelerating inserts [Ref. 16]. This bulk, concentrated at the gun to work interface severely limits process adaptability. Poor control of gun to work distance and welding speed limit the pool or keyhole stability. Limited line tracking capability, attributable to bulk and to limited pool visibility further handicap the process.

The device built by Hamilton Standard [Ref. 16] was tested in a man-rated vacuum chamber. The device produced a maximum penetration of 5 mm in Al and Ti weldments, and 6.5 mm in stainless steel. The device was operated at 1.5 kW. Researchers have studied NdYAG welds in microgravity environments [Ref. 17]. Welds were produced on stainless steel foils (0.127 mm), weld width was 0.300 mm. The laser yielded only 40 W continuous output, but generated so much waste heat that it was limited to a 2% duty cycle.

Laser processes are severely limited by adaptability. Automated, repeatable EVA applications might be manageable but broad spectrum applications are not. The electron beam process is hampered by the ability of human operators to control it. The hollow tungsten process has been used to weld materials ranging from stainless steel to aluminum in terrestrial applications. The hollow-tungsten process is even more adaptable in the pulsed power mode.

Operator and Mission Safety

Laser devices, particularly those operating at the power levels required to produce fusion, can cause injury [Ref. 25, 36]. Fractions of the beam power reflected during operation are substantial, particularly at startup. Furthermore, the beam is not visible (1.06 μm or 10.6 μm) but can cause eye damage. If the beam strikes nonmetallic materials, its coupling efficiency jumps to well over 90%. Inadvertent targets will be rapidly damaged.

Electron beams are also dangerous. Reflection however, is not a problem. Only direct beam incidence will produce material damage in short time frames. Radiation is produced when the electron beam strikes a target. For 20 kV electrons, this takes the form of x-rays produced by bremsstrahlung and of characteristic emissions from the base material [Ref. 37].

All processes will produce vapor from the weld pool. Eagar [Ref. 38] has demonstrated that more volatile elements are over represented in pool vapor. Kahn, DeBroy and David [Ref. 39] showed that the rate of vaporization increased with increasing laser power, but that the effect of this loss on pool chemistry was most acute at low power when pool size was limited. Furthermore, vaporization increased and pool size decreased as the welding speed increased. Vapor generation from electron beam applications will follow similar trends. Experiments at Hamilton Standard showed a increase of pressure within the radiation shield from 0.00001 to 0.01 torr in a short period. This led to arcing in the electron gun and the development of a radiation safe venting mechanism.

Kahn et al. [Ref. 39] have demonstrated that the vaporization rate for laser welds on stainless steels in the range of 0.2 to 4 kW ranges from 10 to 50 ug/min. They further indicate a gross variability with alloy type, high Mn stainless steels being more susceptible to mass loss. Eagar reported similar trends in vaporization rate and vapor character for GTAW welds on Al based alloys. He observed evaporation rates of from 60 to 800 ug/min in aluminum alloy for a 2 kW arc. Evaporation rates in aluminum welded with the laser process would exceed these values.

Small amounts of inert gas would be placed in the vicinity of the weld by the hollow tungsten process. This gas would rapidly dissipate, and would pose no danger to structures. No oxygen would be released by any of these welding processes, save that outgassed by workpiece materials. The total amount of reactive gas loosed in the EVA would not impact the ambient atomic oxygen levels associated with low earth orbit [Ref. 40-43].

All processes would produce particulates, laser processes would be prone to explosive events in the weld pool if nonmetallic inclusions were present. Heile [Ref. 44] has done some work to characterize the particle size distributions associated with welding operations. These particles would remain hot for a time period inversely related to their surface to volume ratios.

Electromagnetic interference would be produced by hollow tungsten power supplies during arc operation. Severe EMI would be produced by high frequency starting methods. Electron beam apparatus also generate EMI, and high voltages. Several alternate starting methods for the hollow-tungsten process have been developed. Currently, a high-voltage surge is employed.

Process Reliability

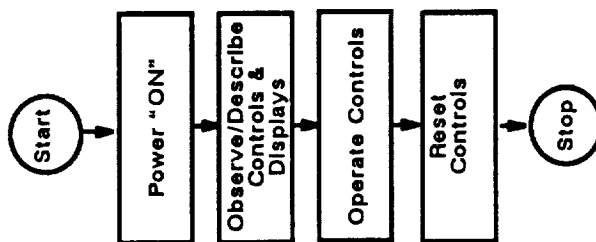
The reliability of each of these systems is high. Replacements to failed parts of any welding apparatus in the EVA would be ill-advised. Items most prone to failure in laser systems are the driving lamps. The electron beam device is limited by the cathode life. In addition this cathode is not durable, and subject to shock damage.

Appendix 2

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A2-1

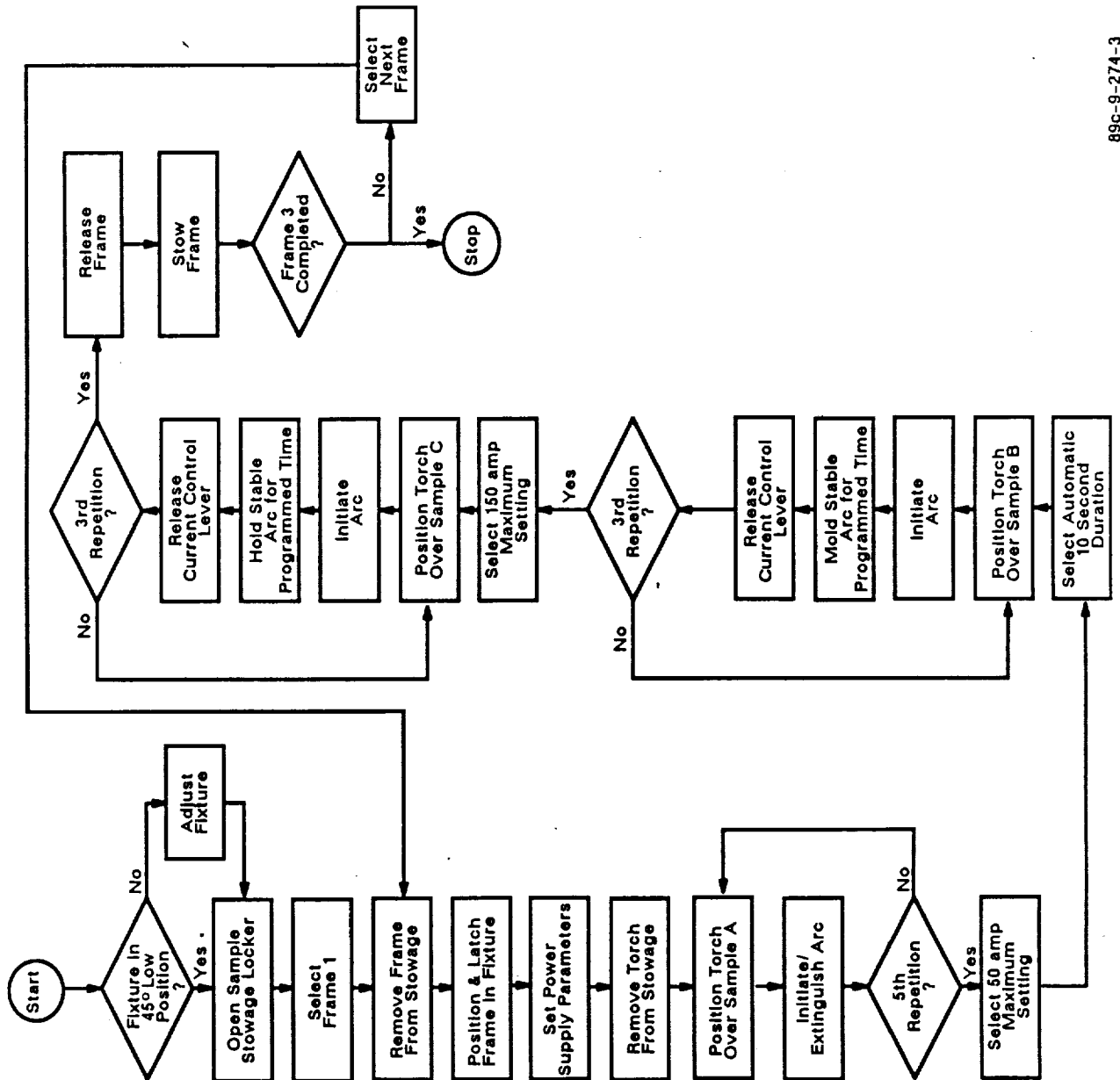
Task 1



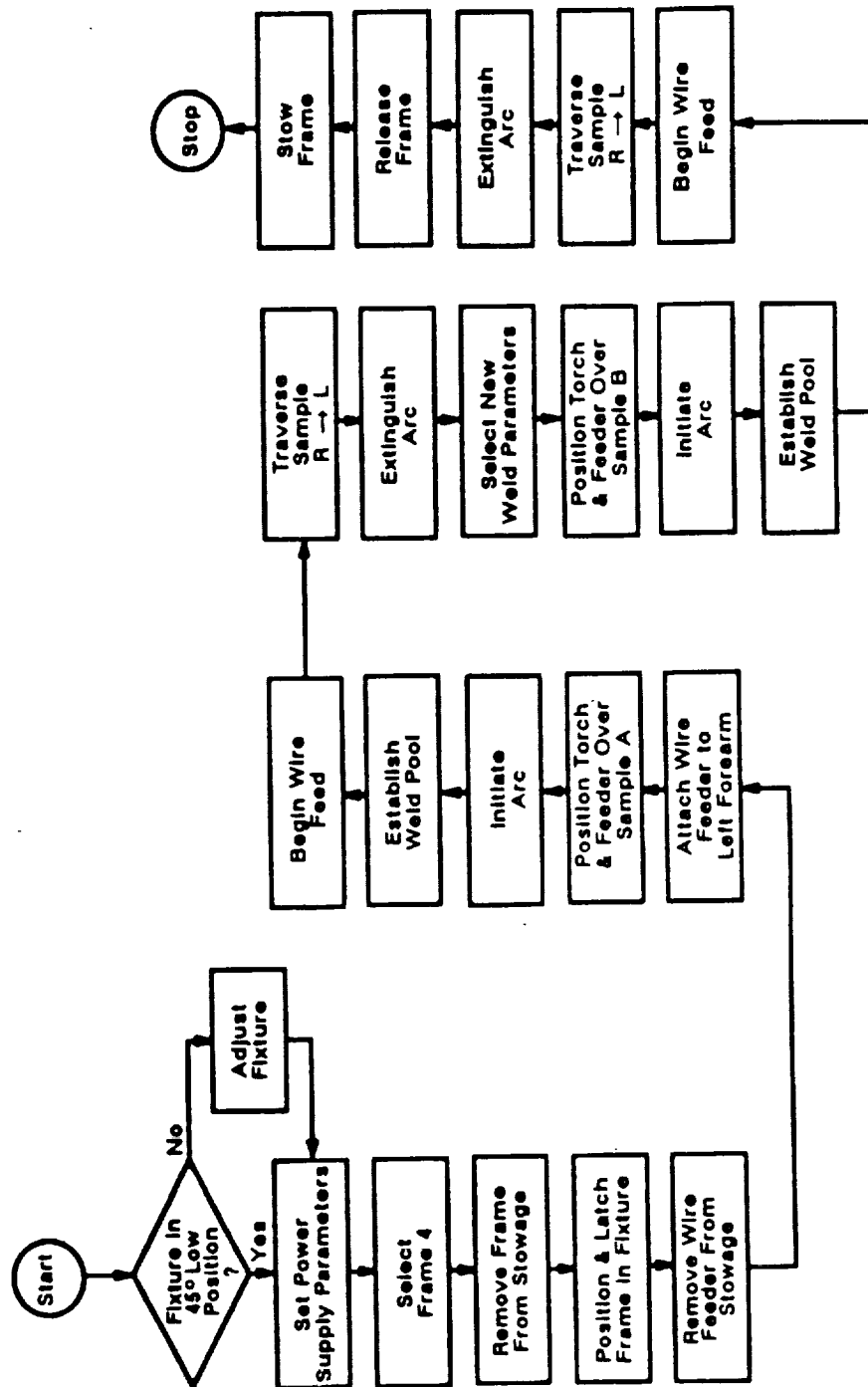
Task 2

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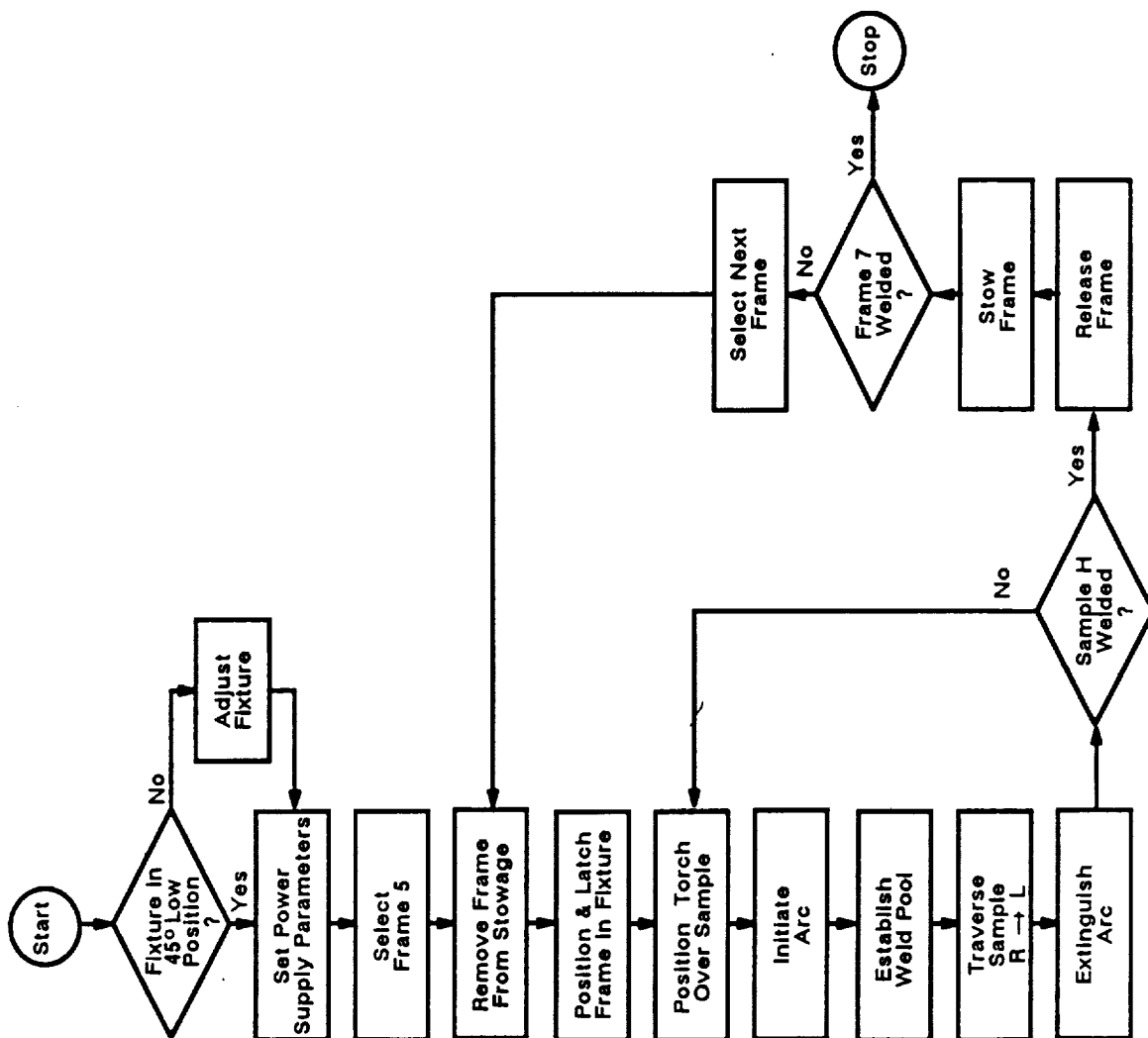
Task 3



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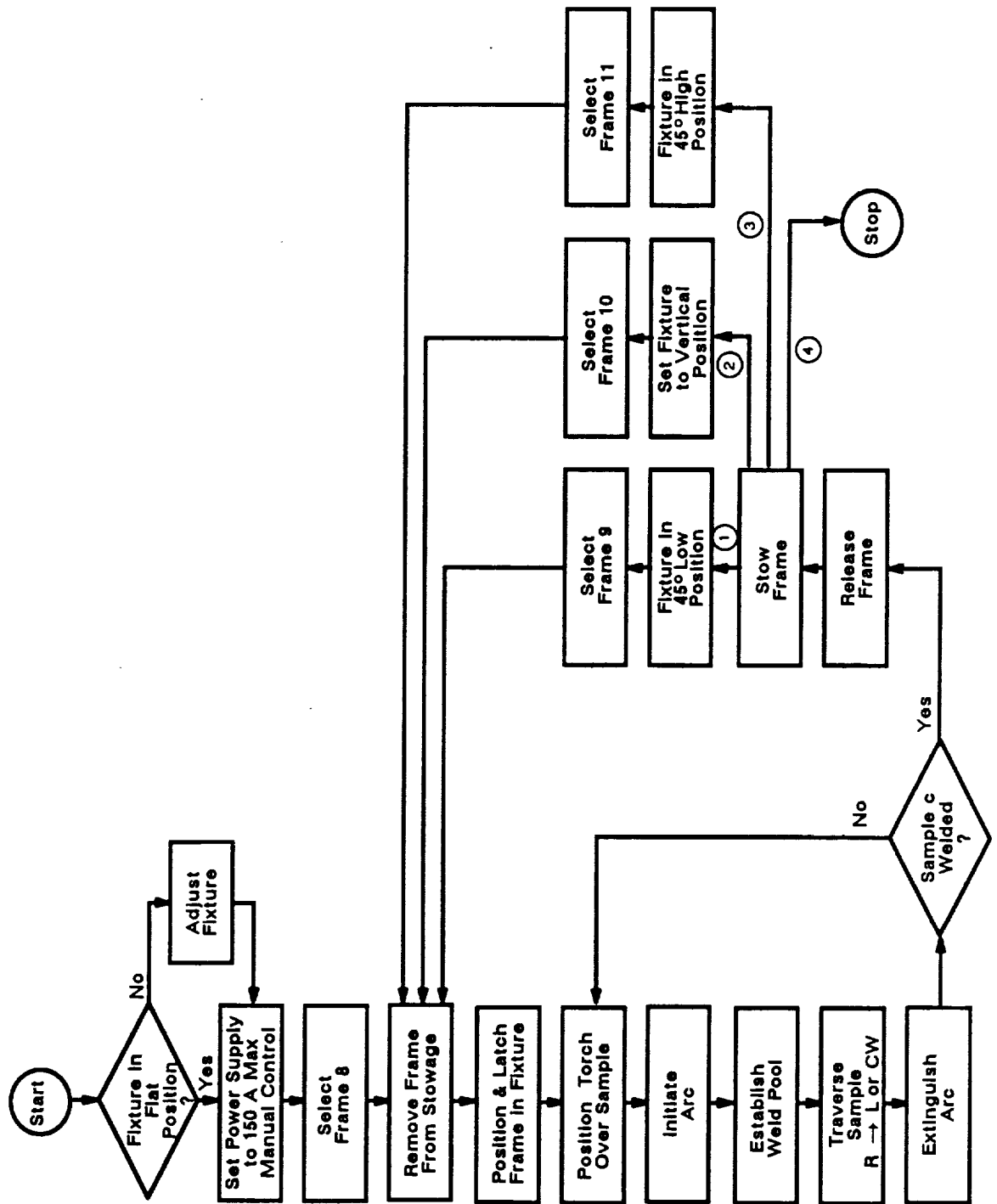
Task 4



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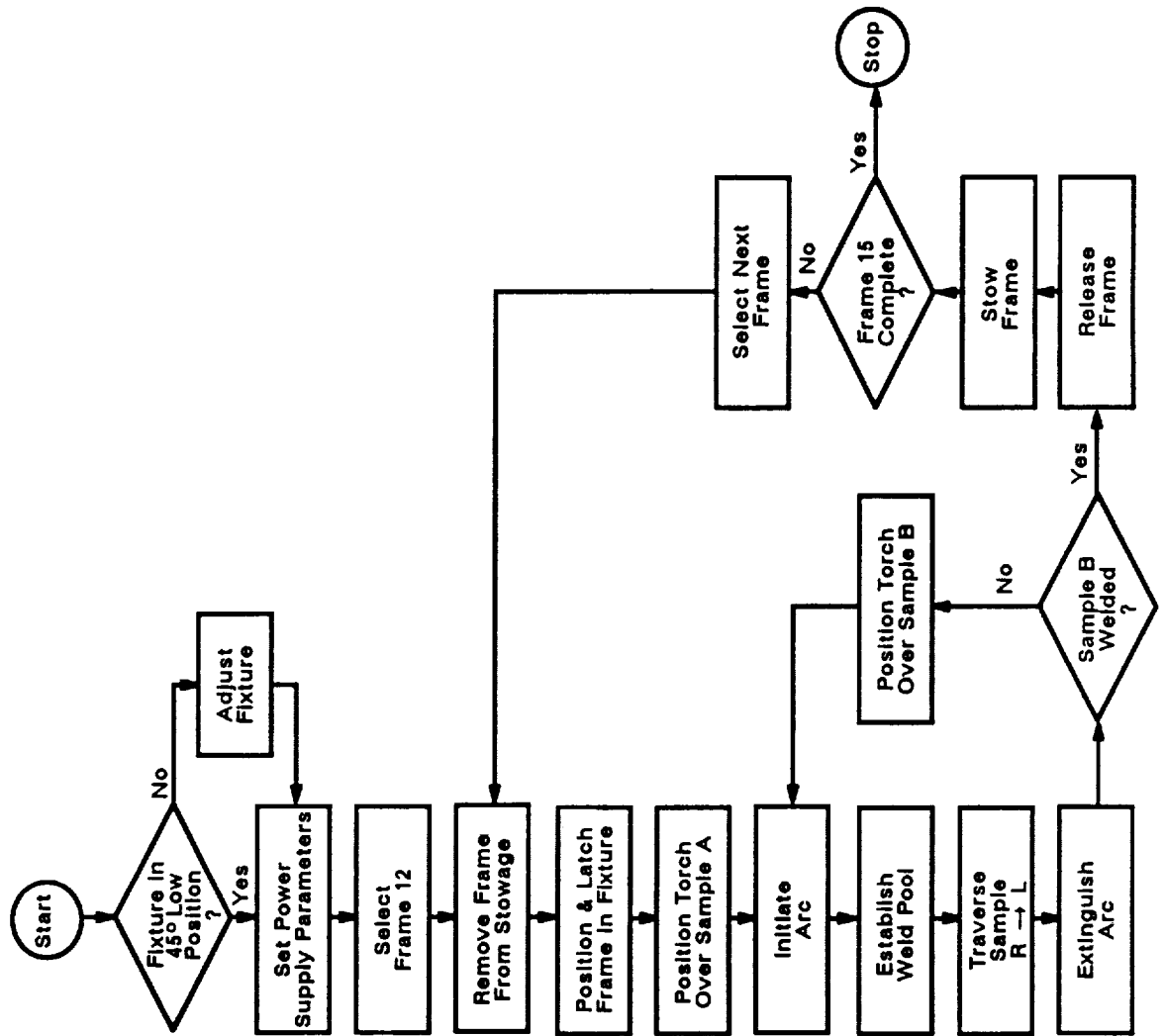
Task 5



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Task 6



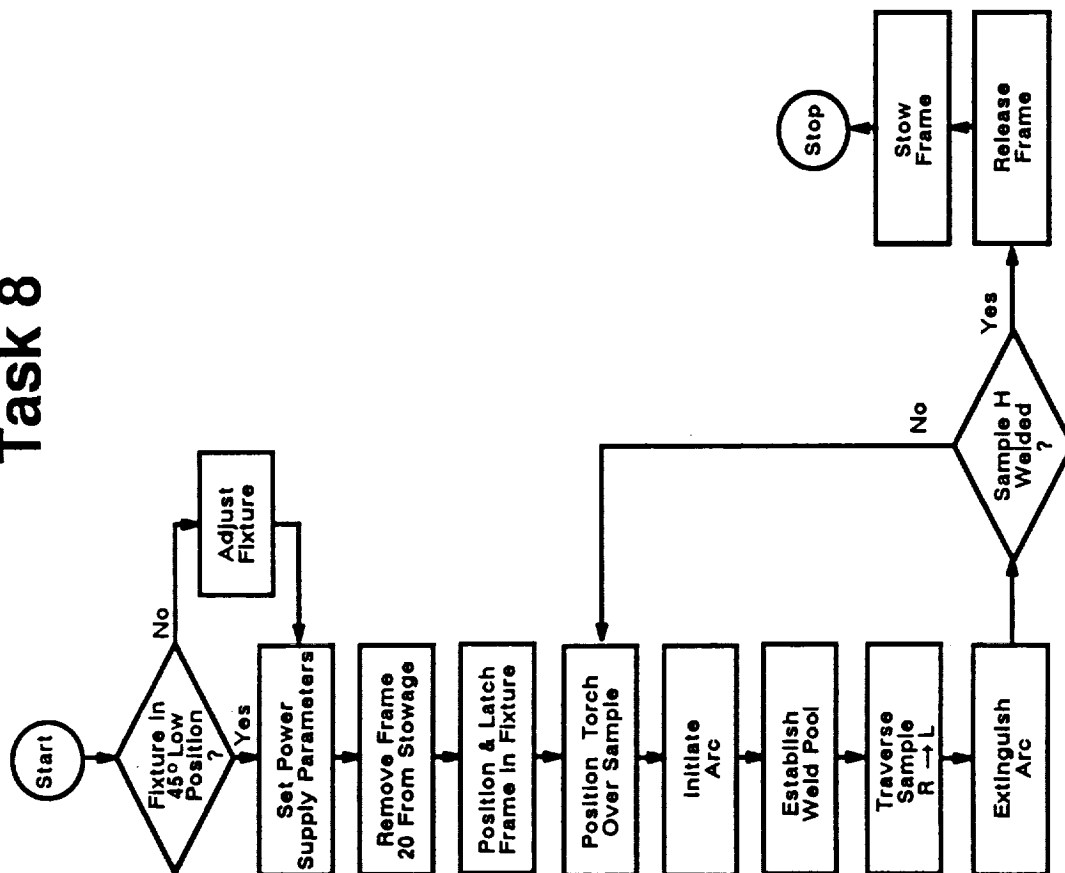
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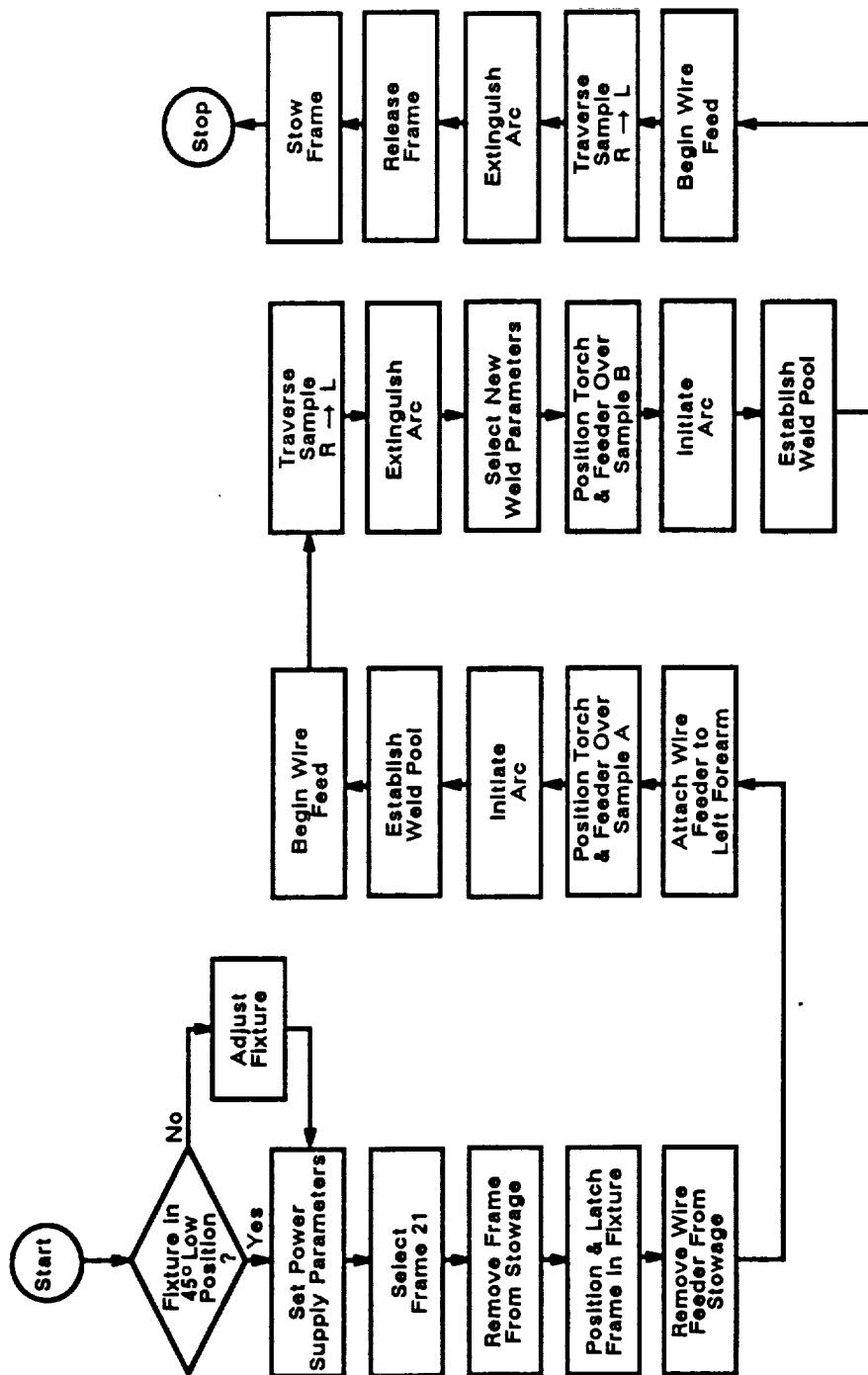
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Task 8



Task 9

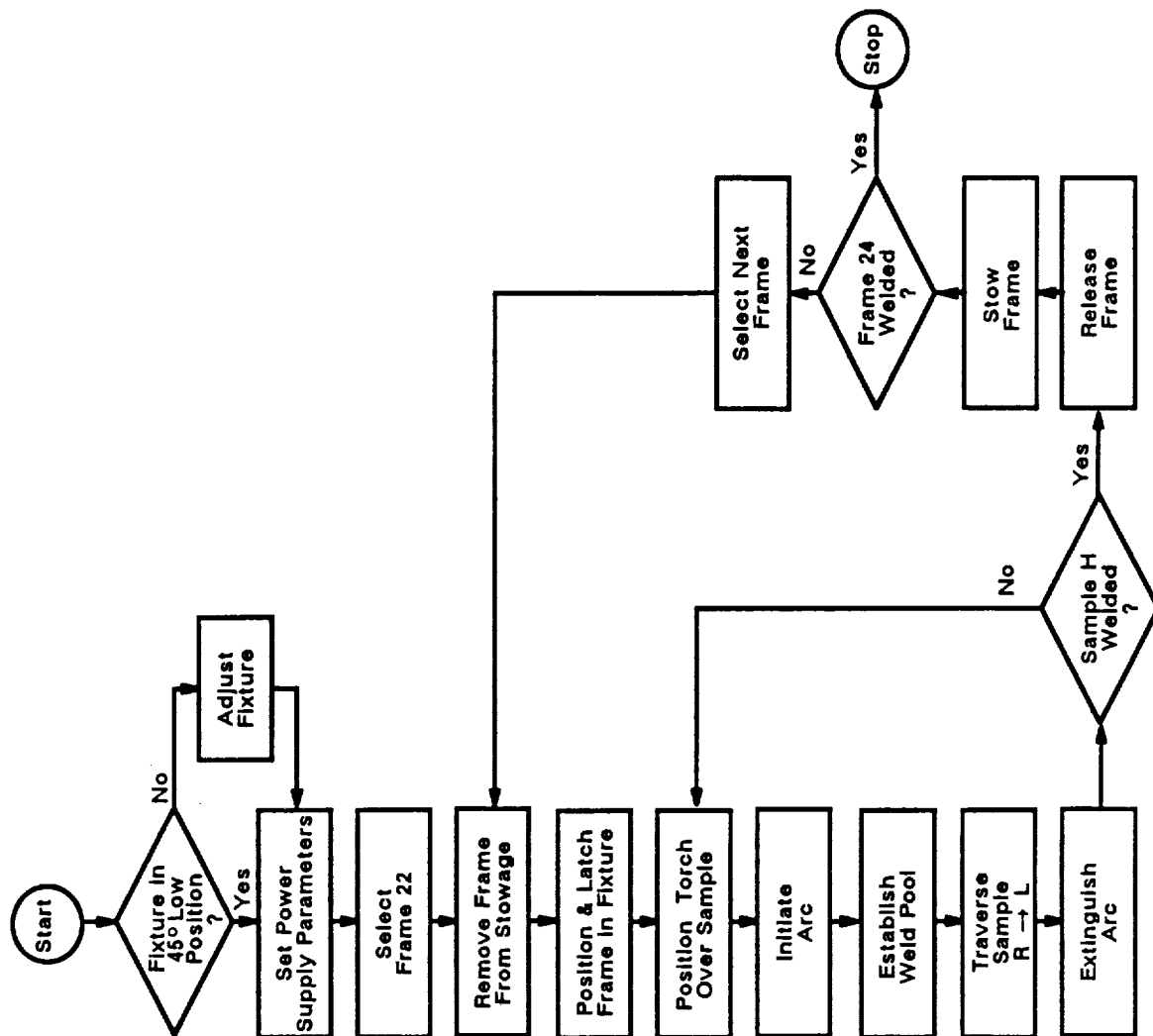


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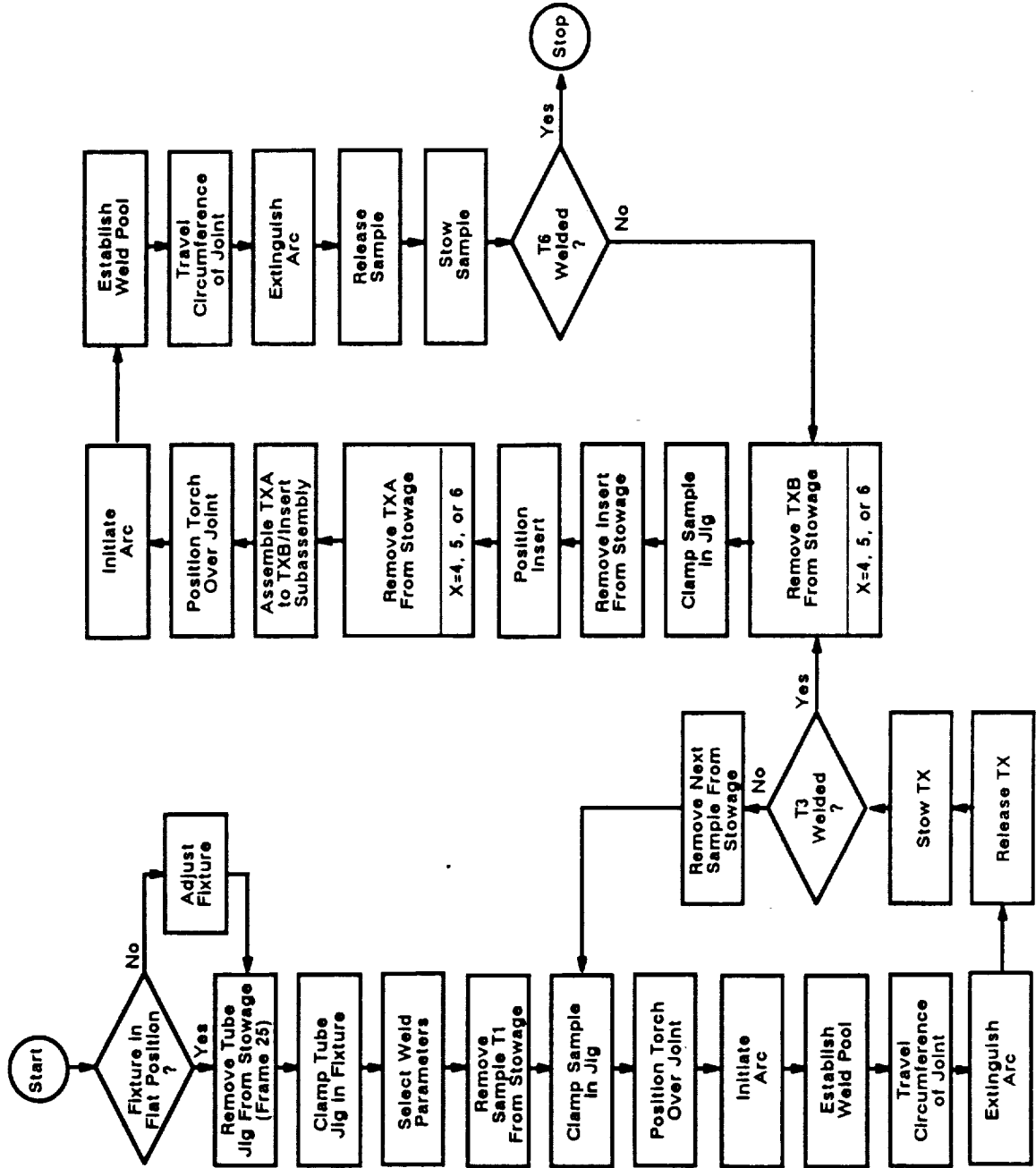
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Task 10

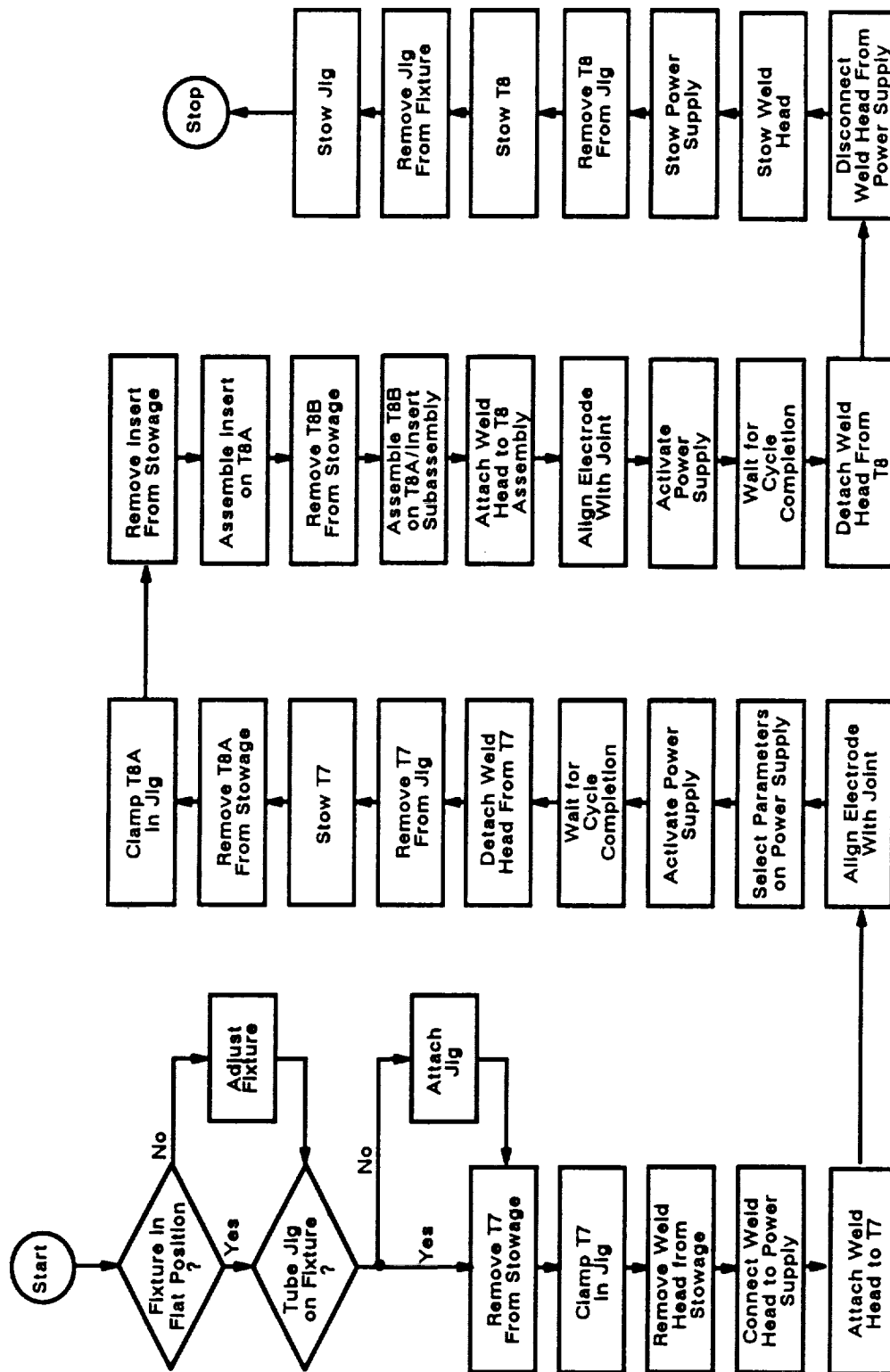
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Task 11



Task 12



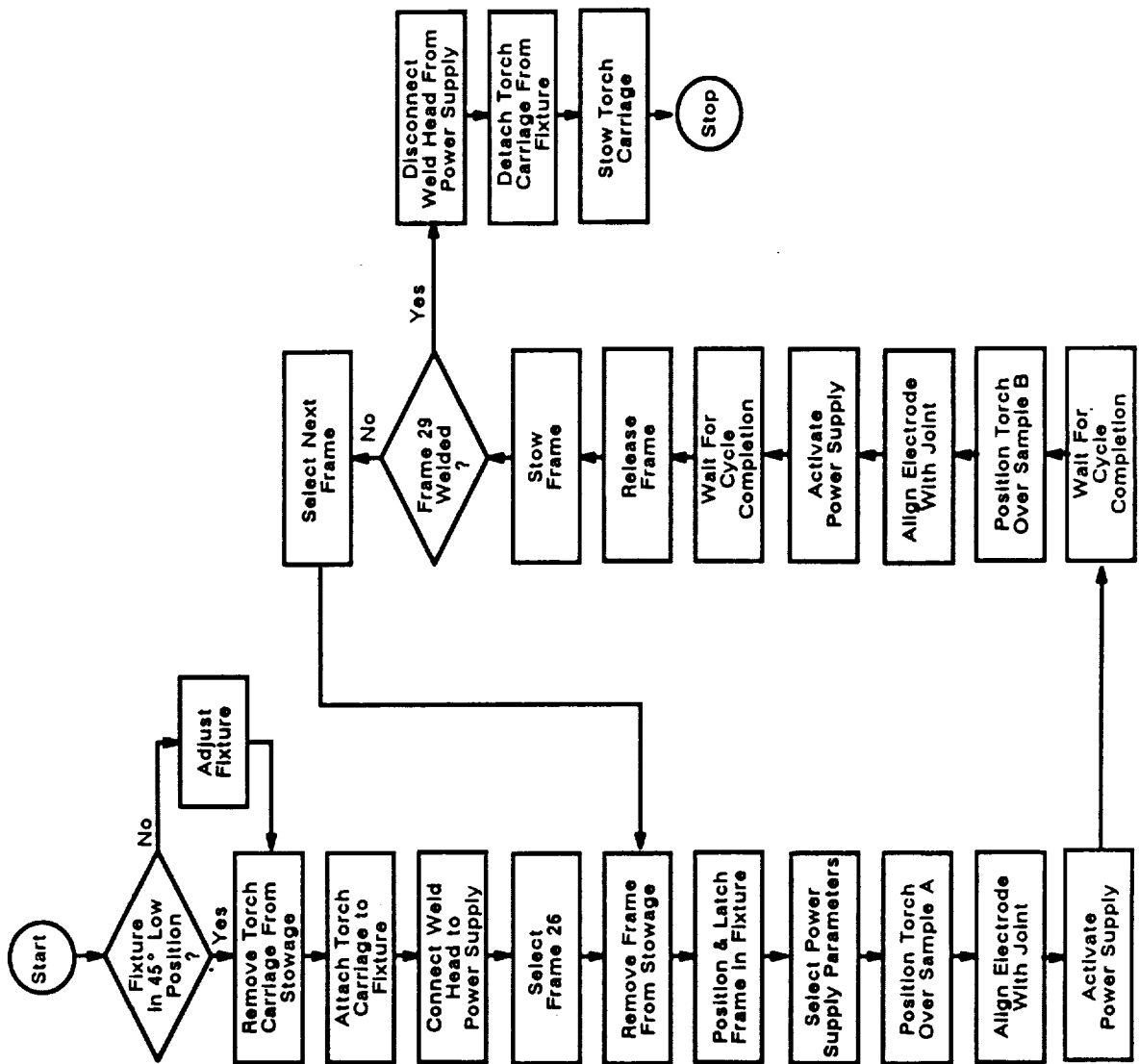
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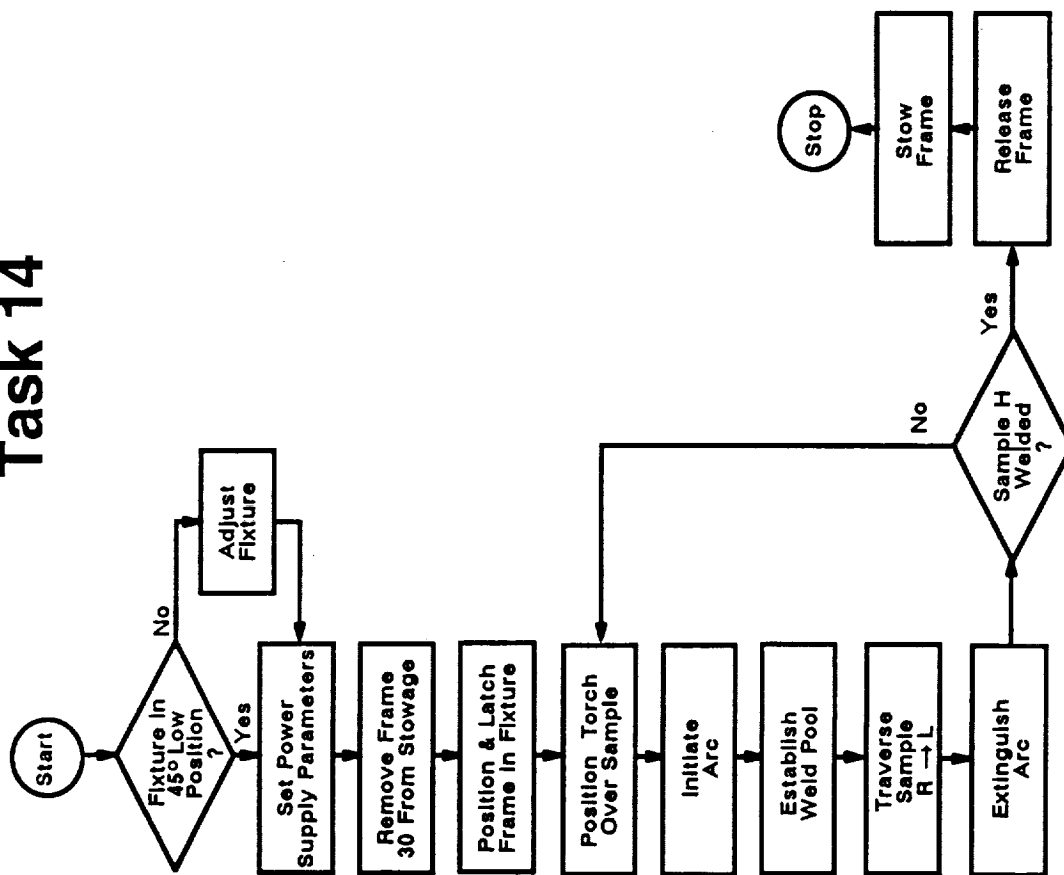
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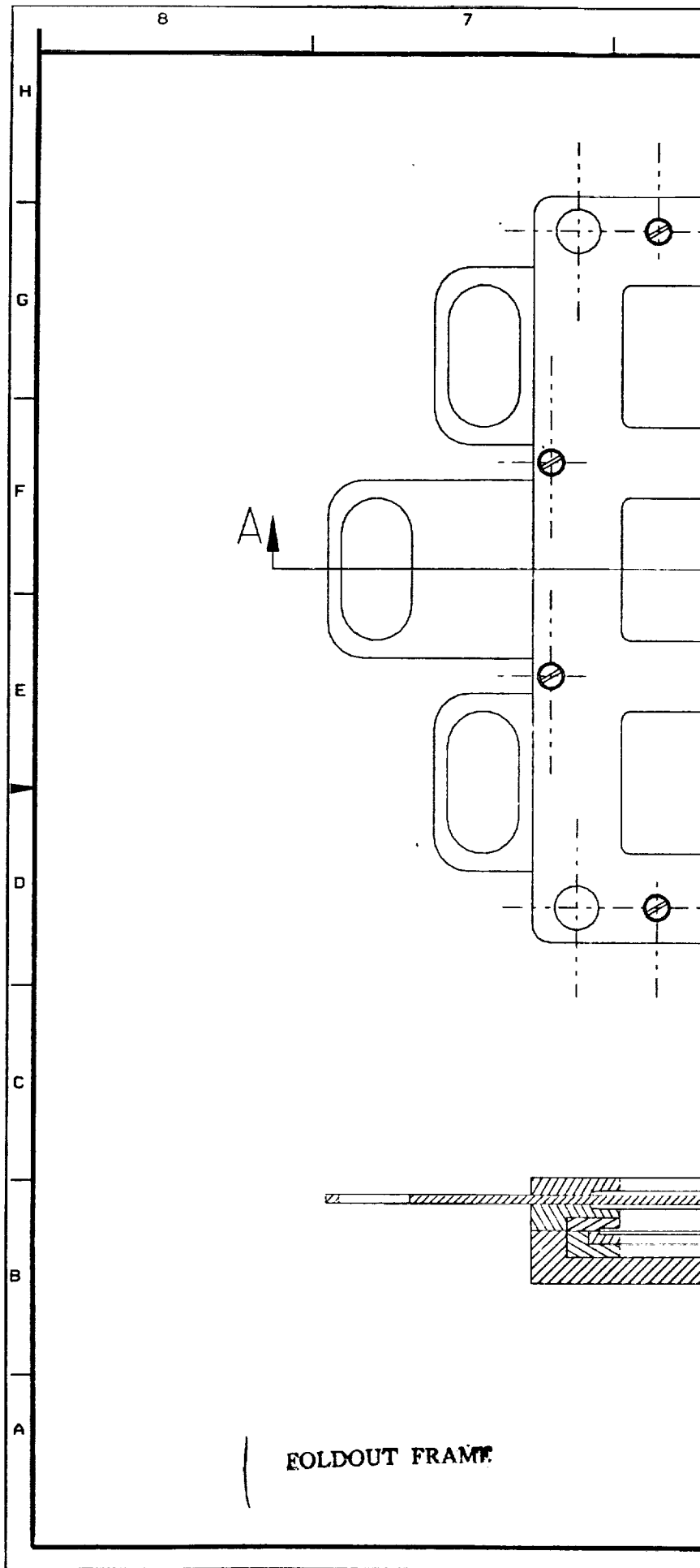
Task 14

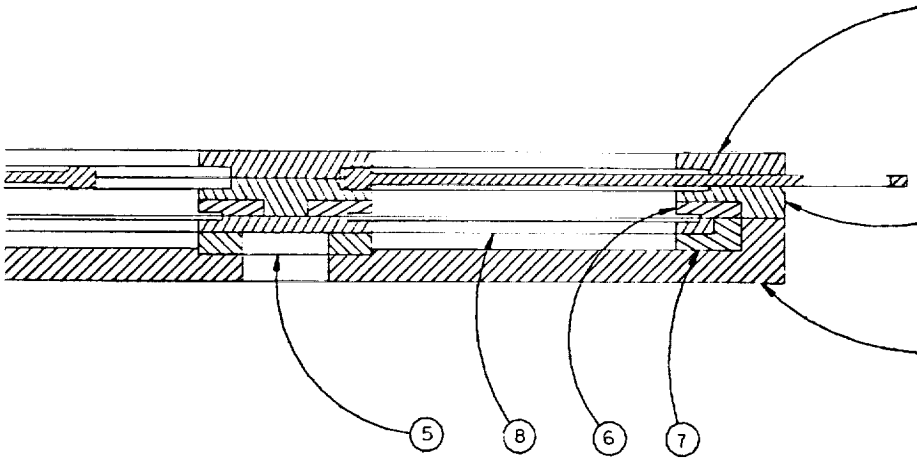
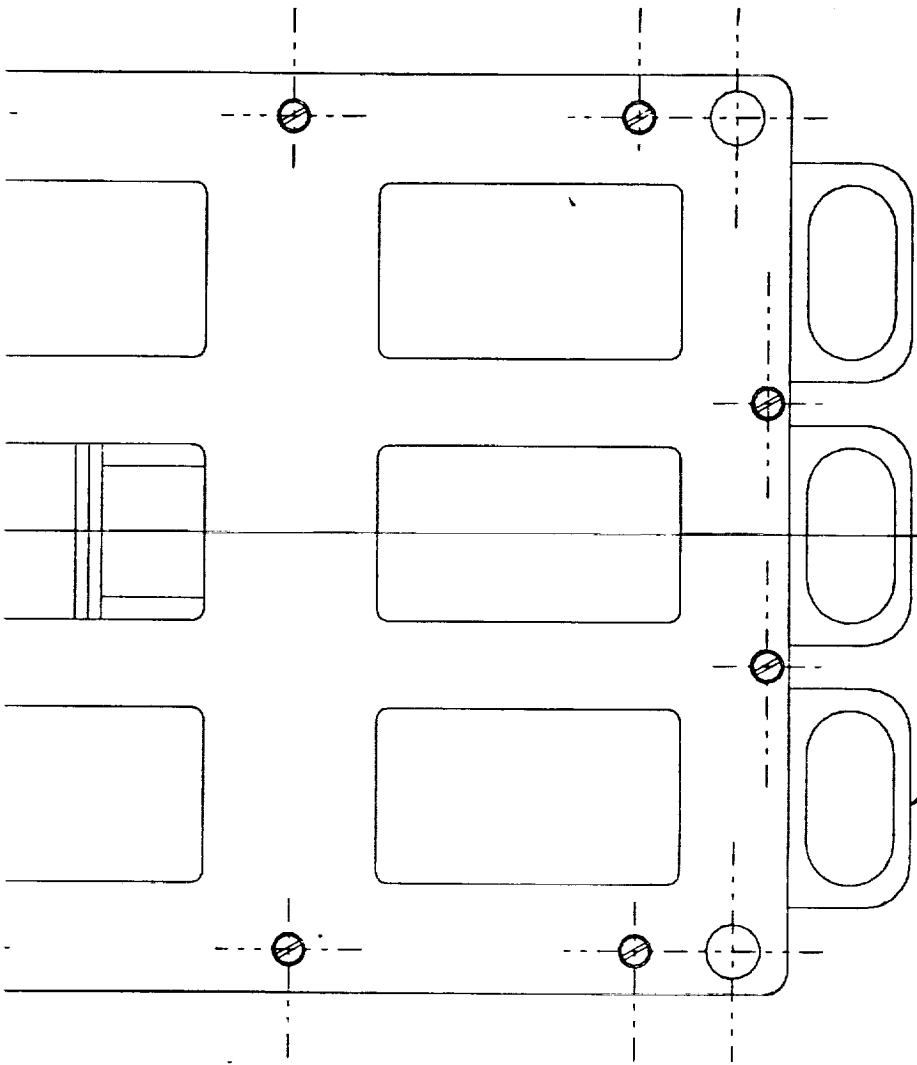


Appendix 3

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A3-1





SECTION A-A

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2 FOLDOUT FRAME

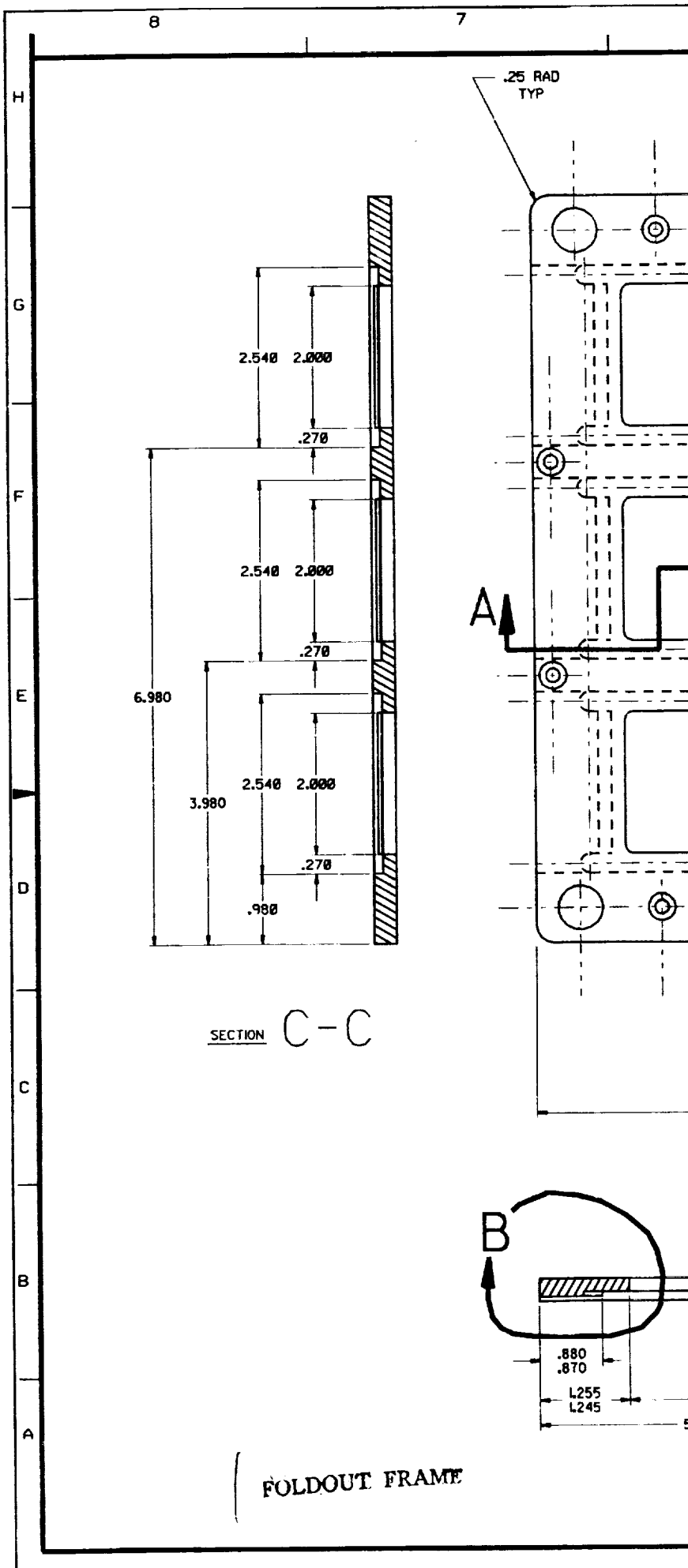
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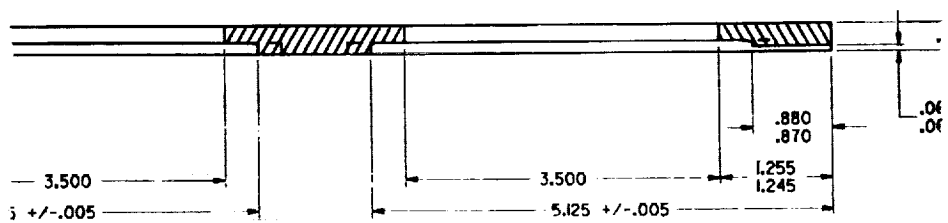
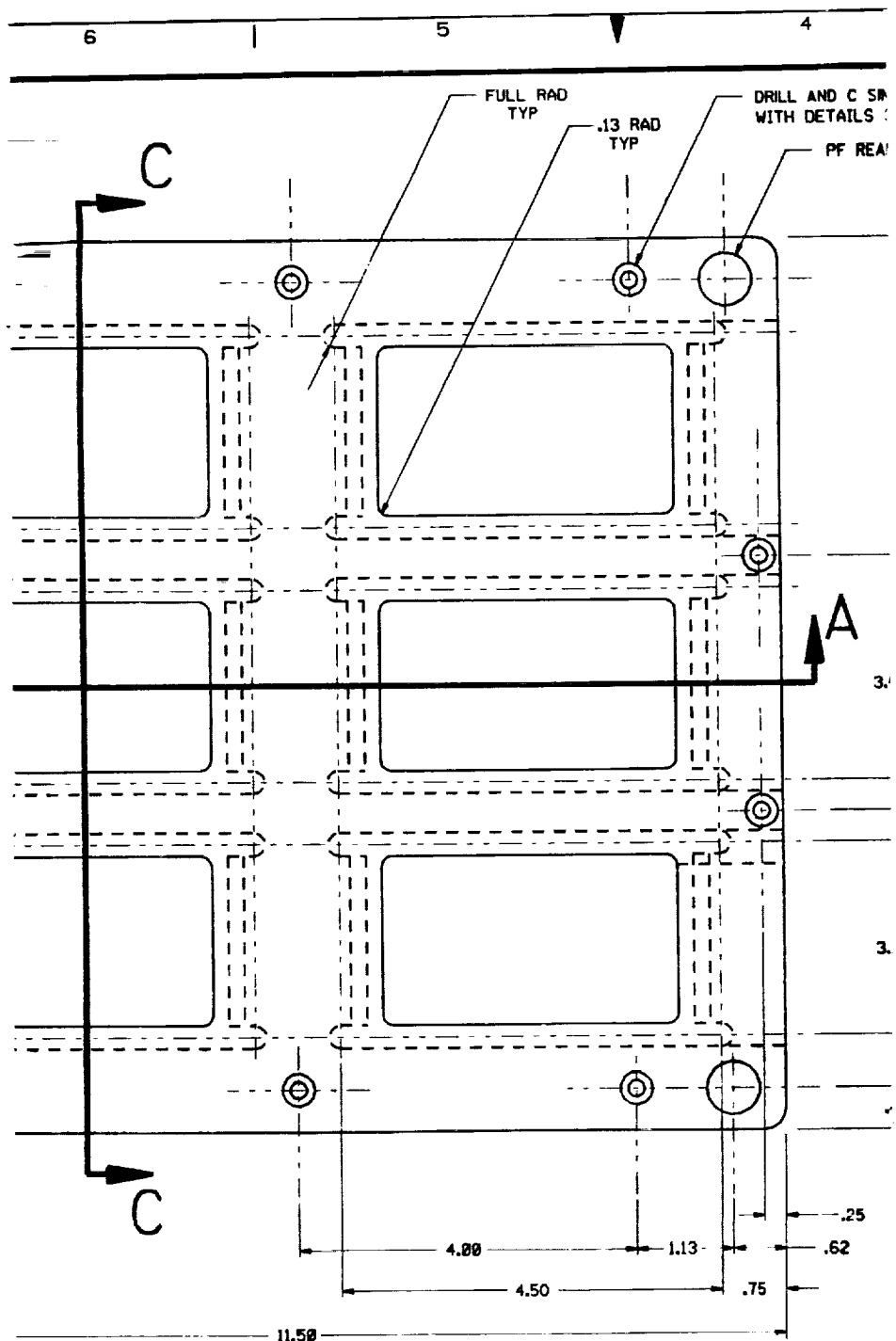
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FIND NO.	SHEET NO.	NO. REQD	DESCRIPTION	MSFC 13VAXI FILE QSAH[64,5]..*
8	6	1	GROUNDING PLATE	KCI35.S06
7	5	2	BOTTOM EDGE INSULATING STRIP	KCI35.S05
6	5	4	TOP EDGE INSULATING STRIP	KCI35.S05
5	5	1	CENTER INSULATING STRIP	KCI35.S05
4	5	6	SLIDE COVER PANEL	KCI35.S05
3	4	1	BASE PLATE	KCI35.S04
2	3	1	MID PLATE	KCI35.S03
1	2	1	TOP PLATE	KCI35.S02
	1		ASSEMBLY DRAWING	KCI35.S01

APPROVALS			OVERALL SIZE (REF.)	Rockwell International Corporation	
DEPT.	NAME OR LONGHAND	DATE	LENGTH	Rocketdyne Division	
			WIDTH	Canoga Park, California	
			HEIGHT		
			TOOL ENGINEERING		
			TOOL NAME: WELD SAMPLE HOLDING FIXTURE		
			PART NO. _____ PART NAME _____		
			DRAWN _____ DATE _____ CHECKED _____ DATE _____ APPROVED _____ DATE _____		
			INTERIM/PROG CAD DRAWING _____ FILING/NO. (SCALE) (REV) (1) (2) (3) (4) (5) (6) (7) (8) (9) (10) (11) (12) (13) (14) (15) (16) (17) (18) (19) (20) (21) (22) (23) (24) (25) (26) (27) (28) (29) (30) (31) (32) (33) (34) (35) (36) (37) (38) (39) (40) (41) (42) (43) (44) (45) (46) (47) (48) (49) (50) (51) (52) (53) (54) (55) (56) (57) (58) (59) (60) (61) (62) (63) (64) (65) (66) (67) (68) (69) (70) (71) (72) (73) (74) (75) (76) (77) (78) (79) (80) (81) (82) (83) (84) (85) (86) (87) (88) (89) (90) (91) (92) (93) (94) (95) (96) (97) (98) (99) (100)		
			FROM NO. _____ ADDITIONAL SHEETS _____		
			REV. NO. & NO. _____ SCALE _____ T-MRD0070		
			REV. NO. _____		



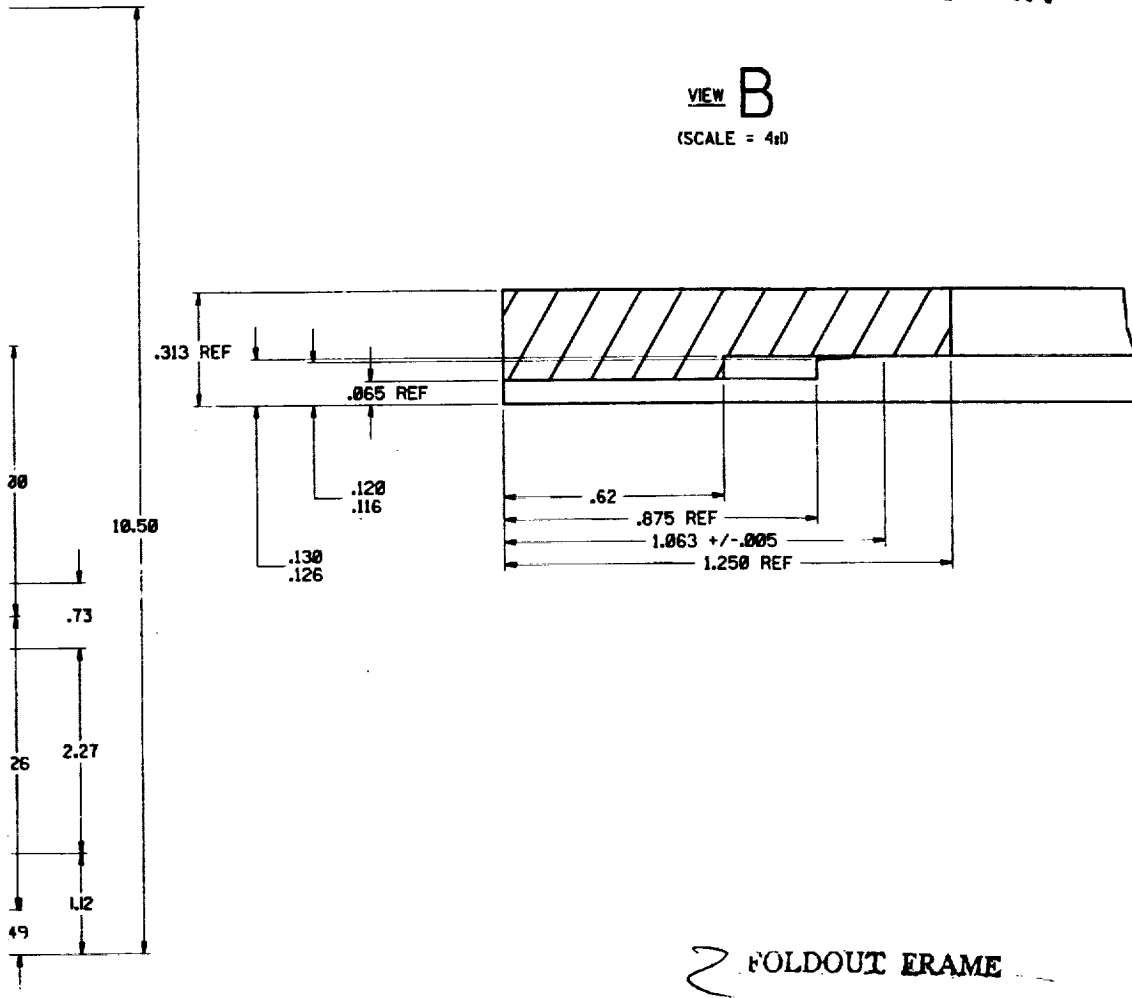


SECTION A-A

K FOR STD #10-24 FLT HD SCREW
 3 & 4, 10 PLCS
 M FOR STD .63 DIA X J88 DP S.STL DRILL ROD, 4 PLCS

ORIGINAL PAGE IS
 OF POOR QUALITY

VIEW **B**
 (SCALE = 4x1)



FOLDOUT FRAME

① TOP PLATE

NOTES:

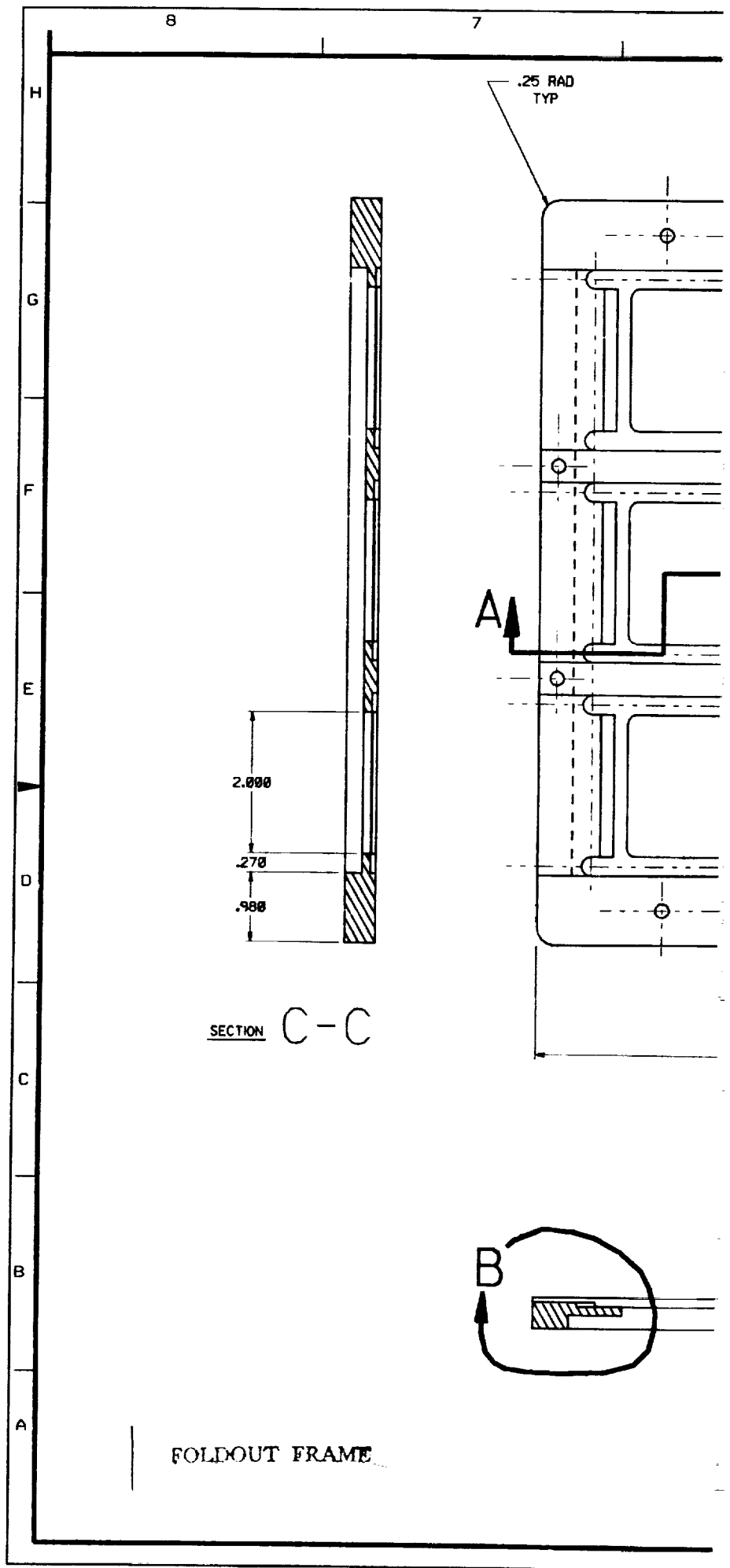
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- ✓ FINISH.
- MATERIAL: 6061-T6 ALUMINUM

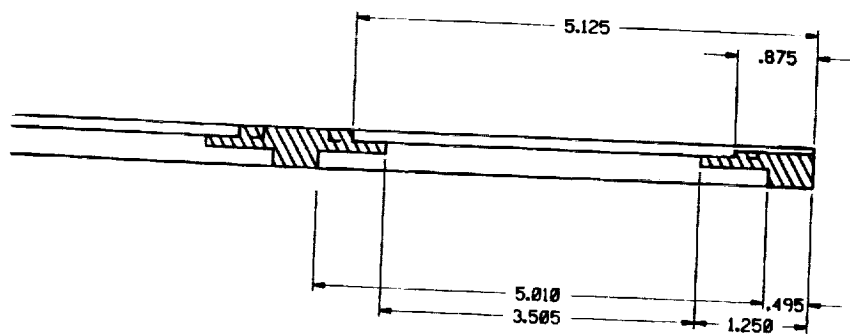
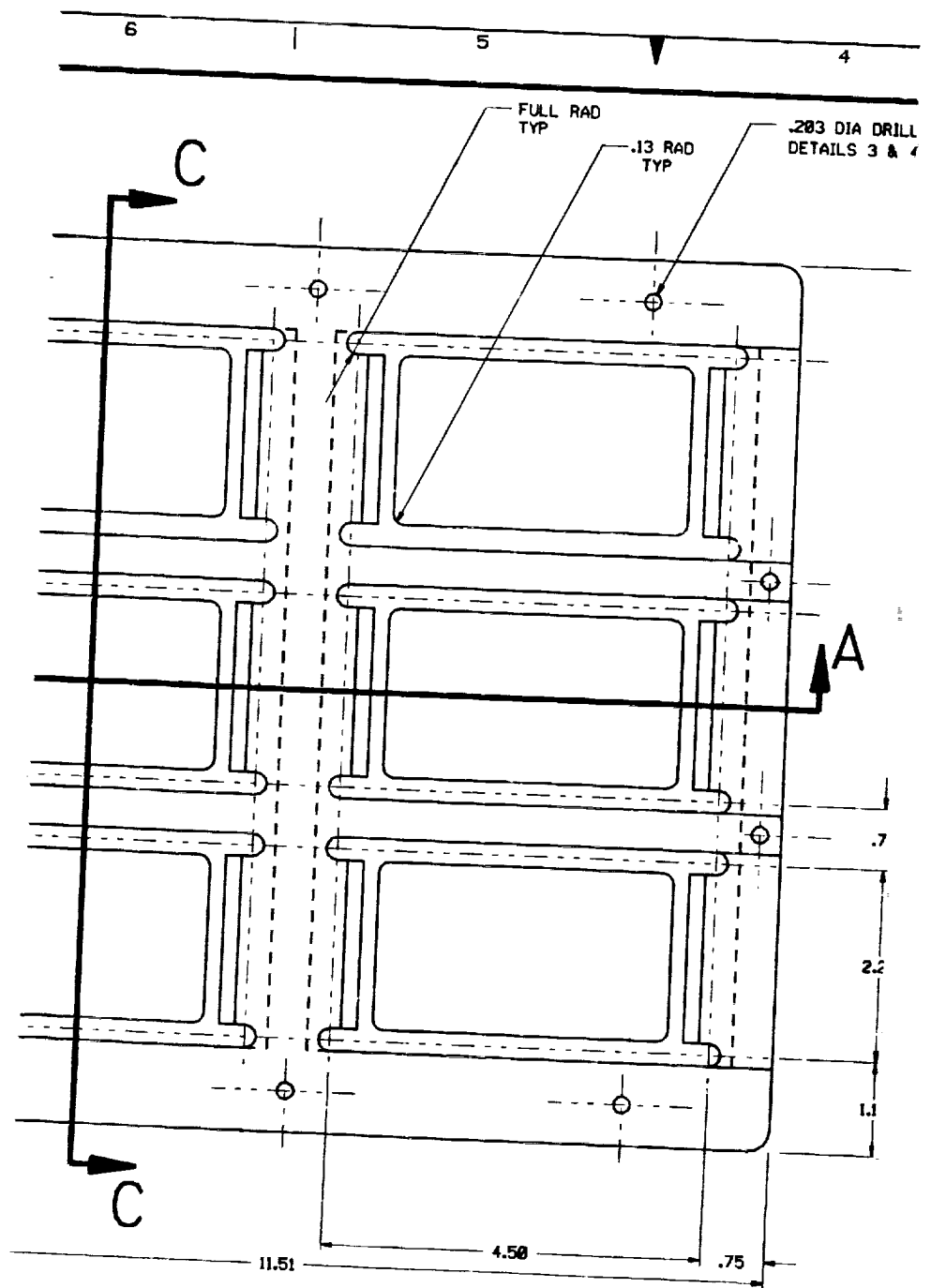
313
 17
 13

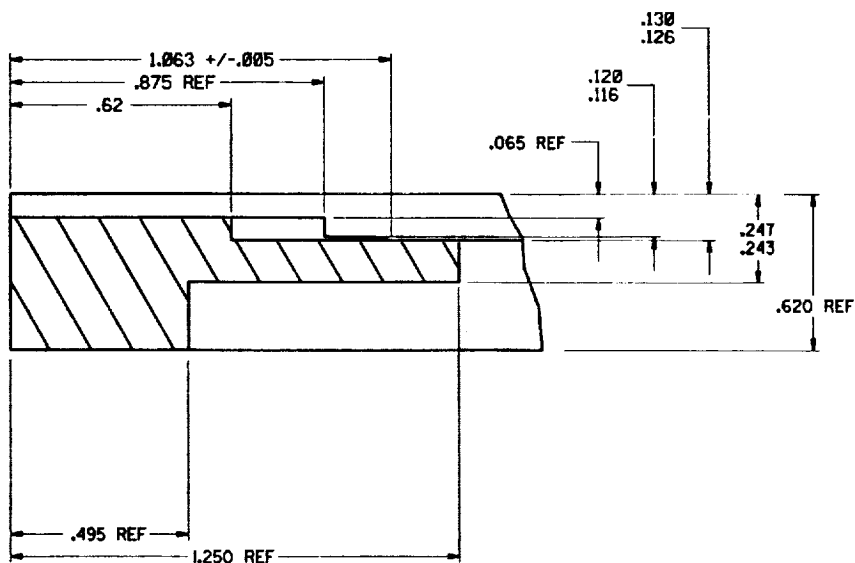
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DEPT.	NAME ON LONGHAND	DATE	LENGTH	WIDTH	TOOL ENGINEERING	
					WELD SAMPLE HOLDING FIXTURE	
			IDENTIFY THIS TOOL AS PROPERTY		TOOL NAME WELD SAMPLE HOLDING FIXTURE	
			TOLERANCES DECIMAL IN INCHES		PART NO. DATE CHECKED DATE APPROVED DATE	
			HOLEX : 1/2" FRACTIONS : 1/8" DECIMALS UNDO : .000		PLANNING : (SHEET 1 OF 1) TOLERANCES : (SHEET 1 OF 1)	
EST. ACT.			WEIGHT VOL. OF PCL.		D-2 1-1 T-MRD0070	

RI/RD89-216

A3-3







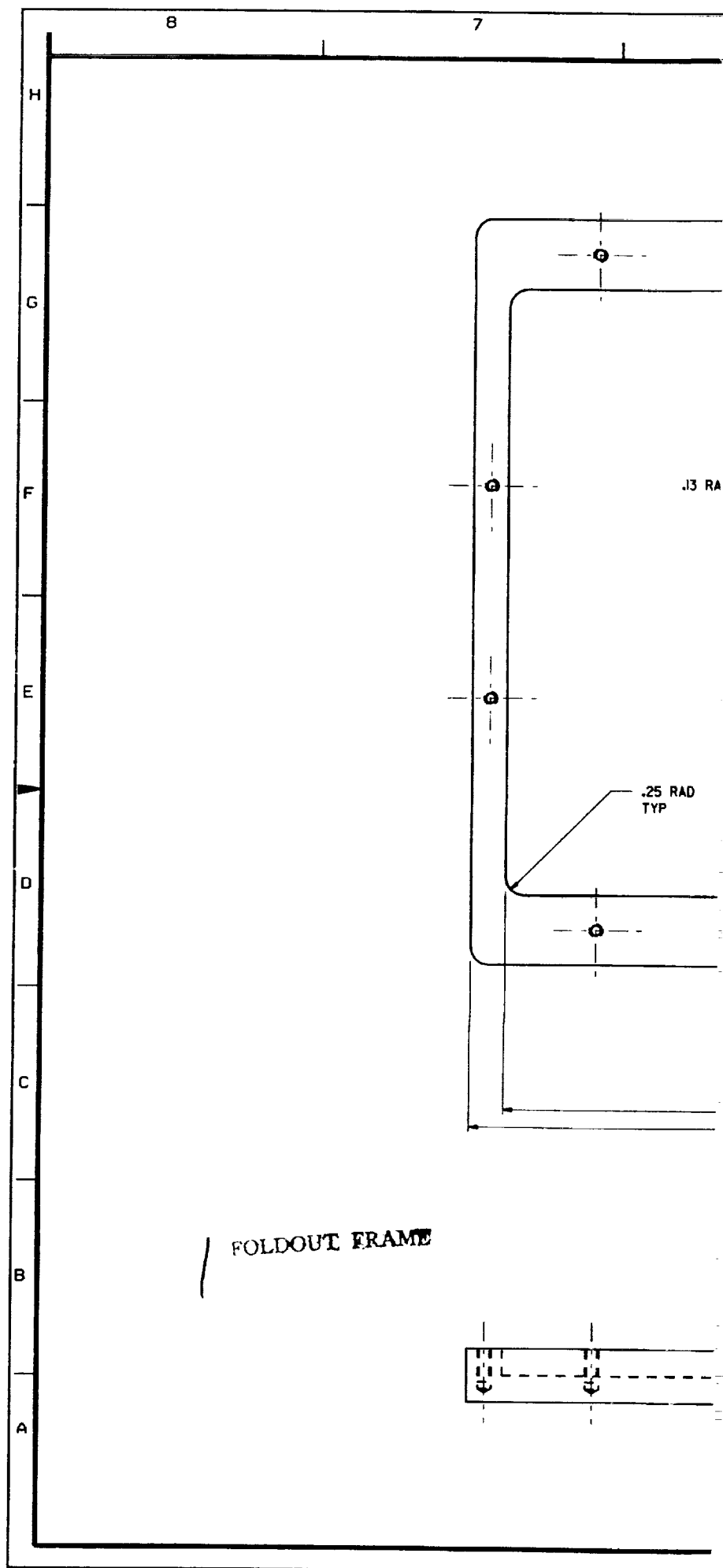
VIEW **B**
(SCALE = 4:1)

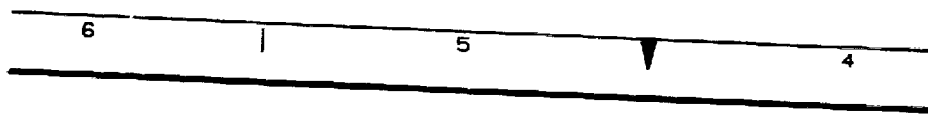
2 FOLDOUT FRAME

2 MID PLATE

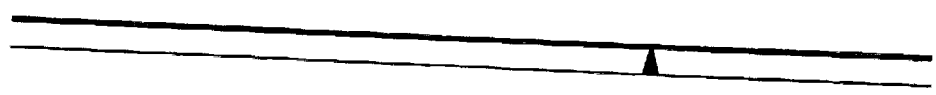
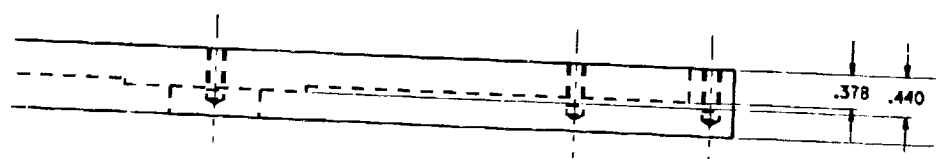
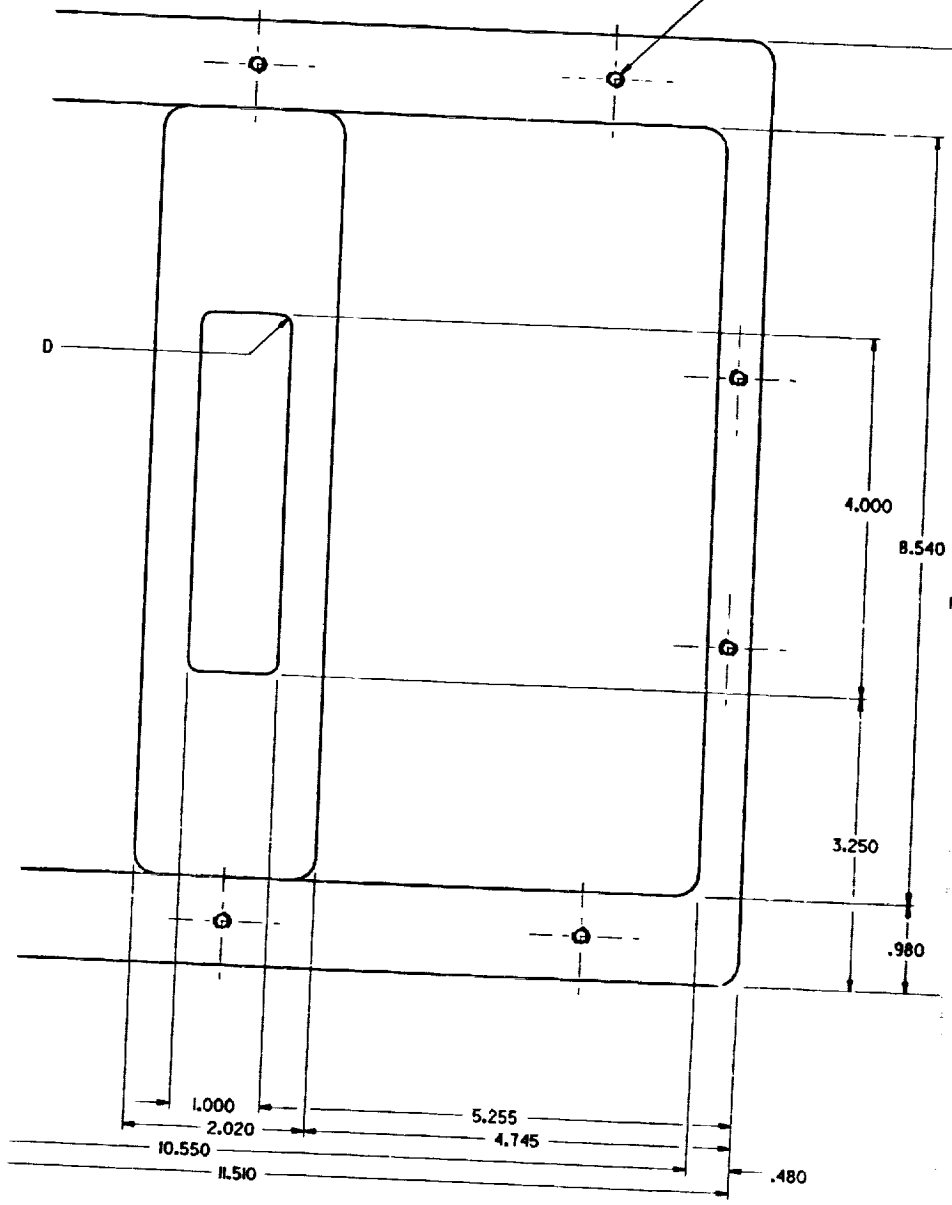
1. BREAK SHARP EDGES. REMOVE BURRS.
2.  FINISH.
3. MATERIAL: 6061-T6 ALUMINUM

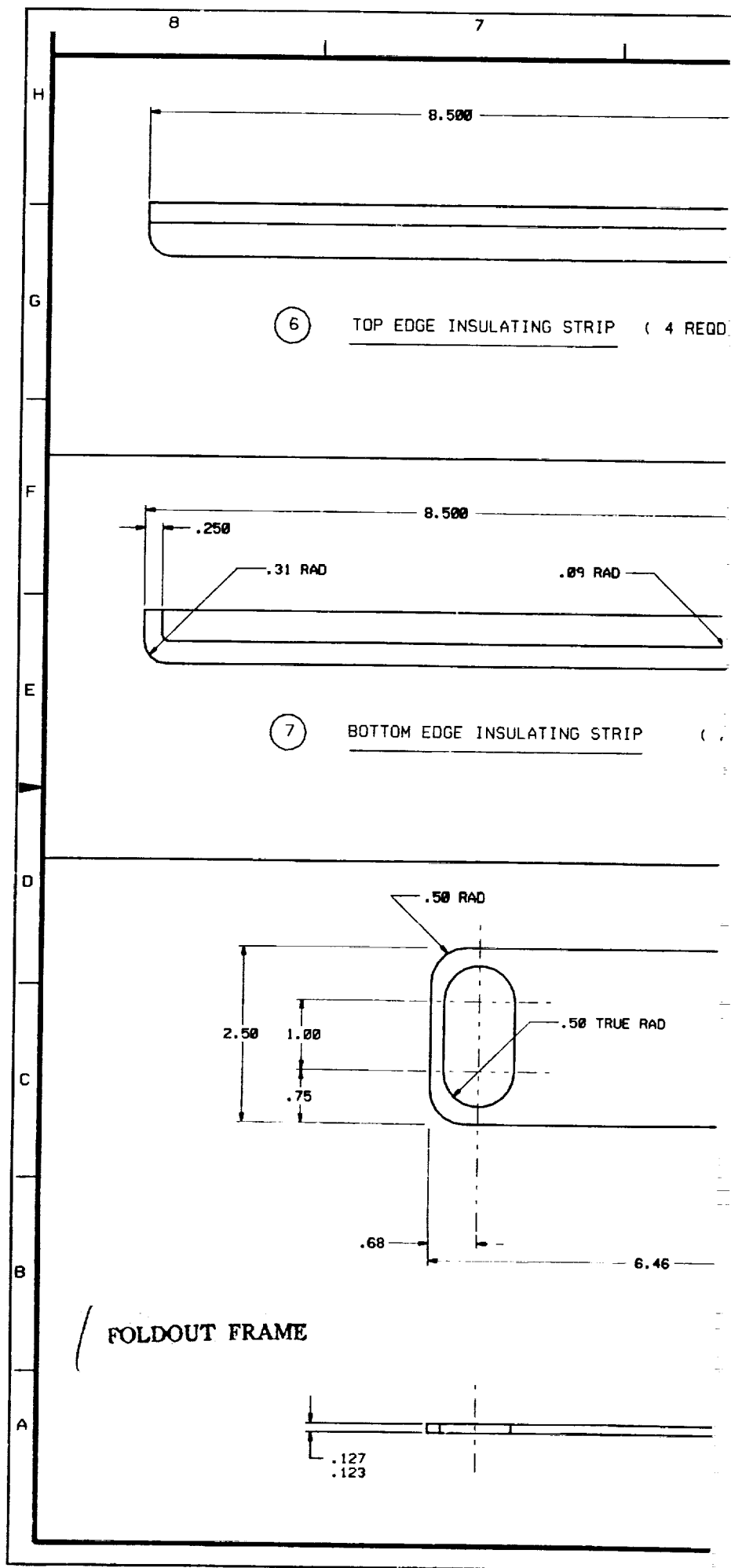
[illegible]





DRILL AND INSERT STD
LOCATE AT ASSY WITH I

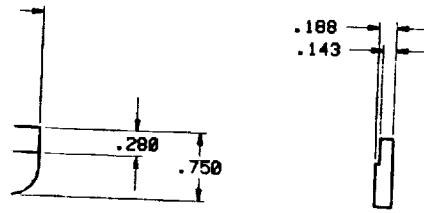




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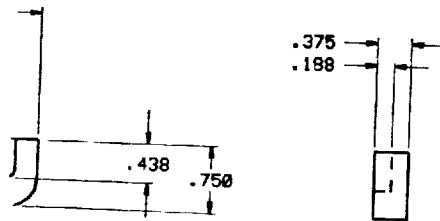
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4



NOTES:

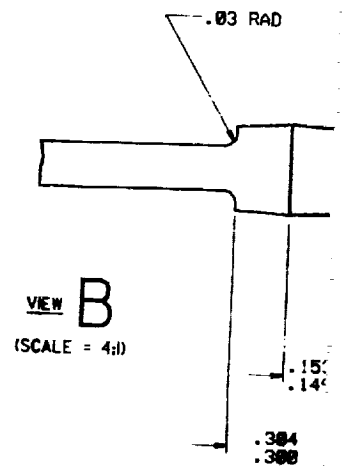
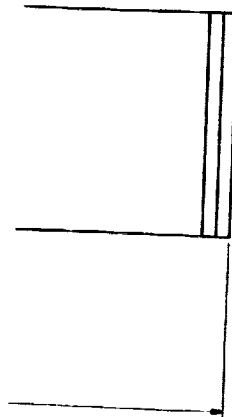
1. BREAK SHARP EDGES. REMOVE BURRS.
2. $\sqrt{}$ FINISH.
3. MATERIAL: TEFLON



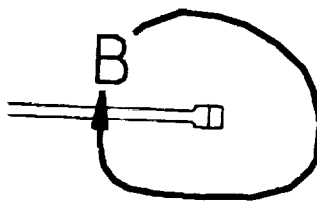
2 REQD)

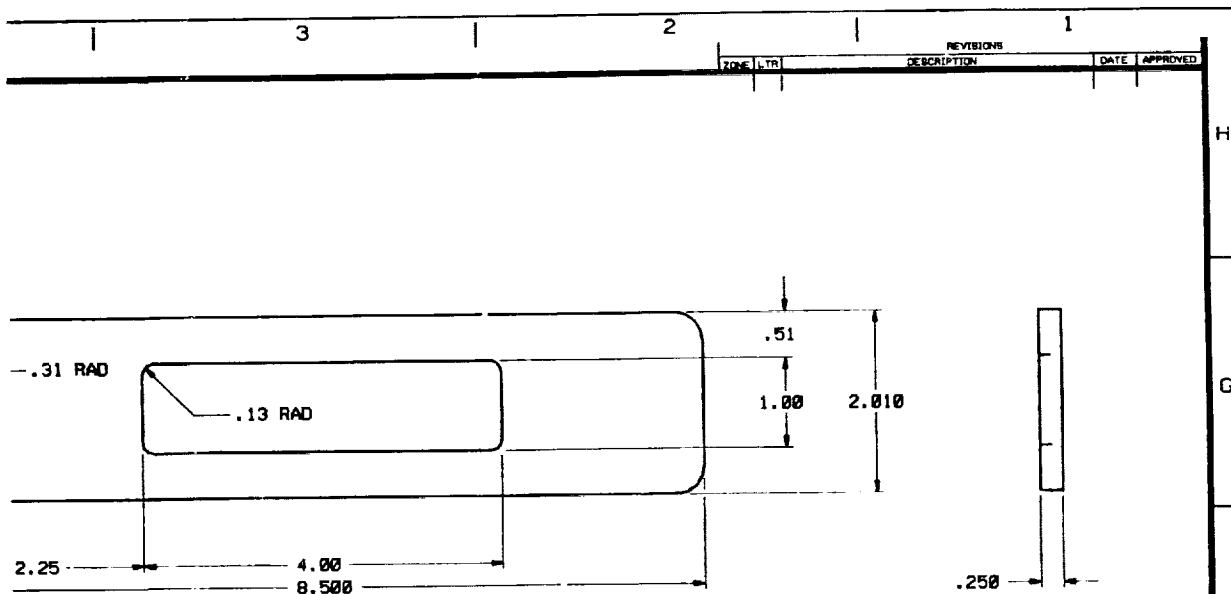
NOTES:

1. BREAK SHARP EDGES. REMOVE BURRS.
2. $\sqrt{}$ FINISH.
3. MATERIAL: TEFLON



VIEW B
(SCALE = 4:1)

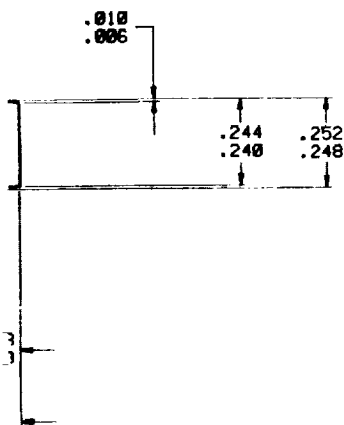




5 CENTER INSULATING STRIP (2 REQD)

NOTES:

1. BREAK SHARP EDGES. REMOVE BURRS.
2. ☒ FINISH.
3. MATERIAL: TEFLON



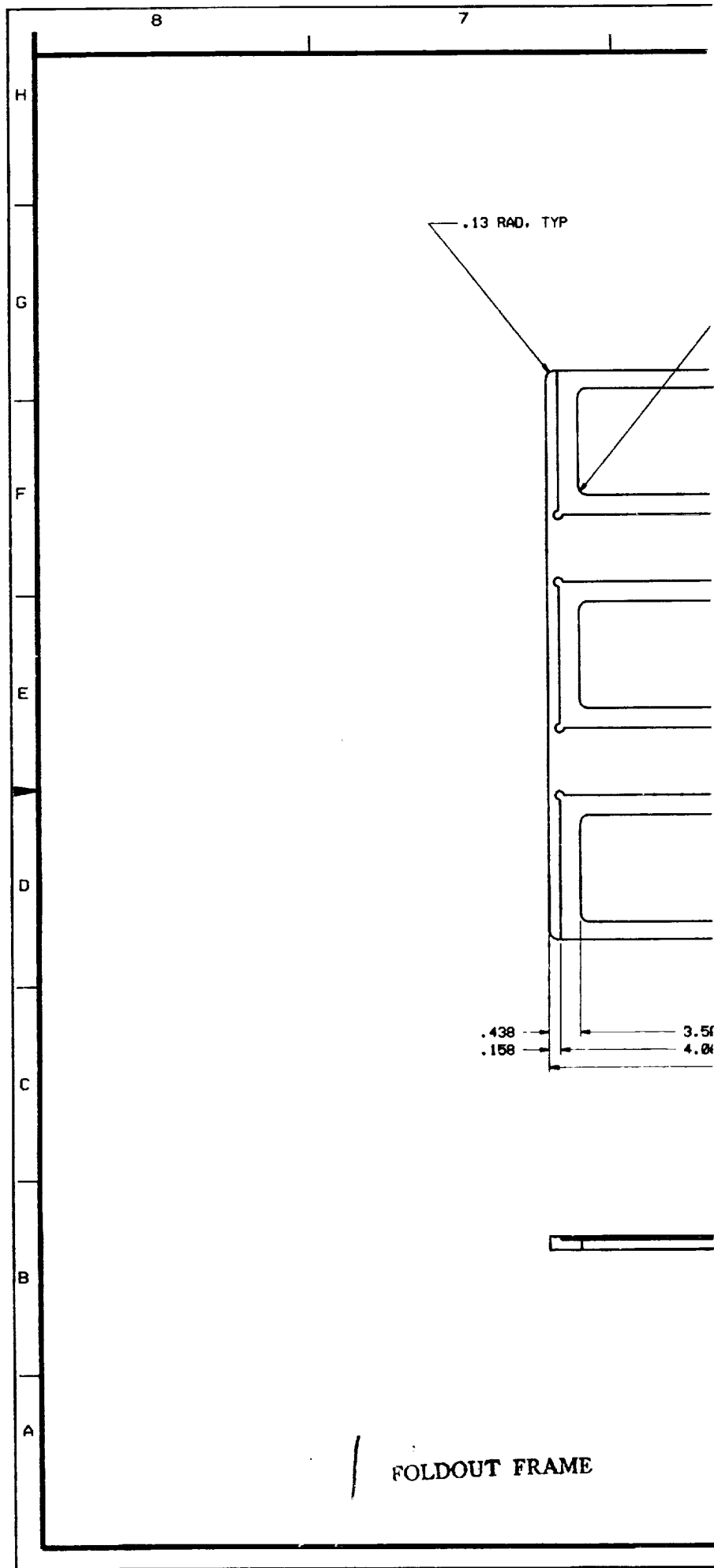
4 SLIDE COVER PANEL (6 REQD)

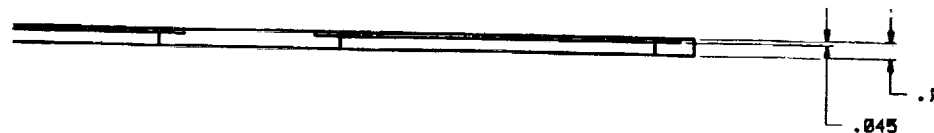
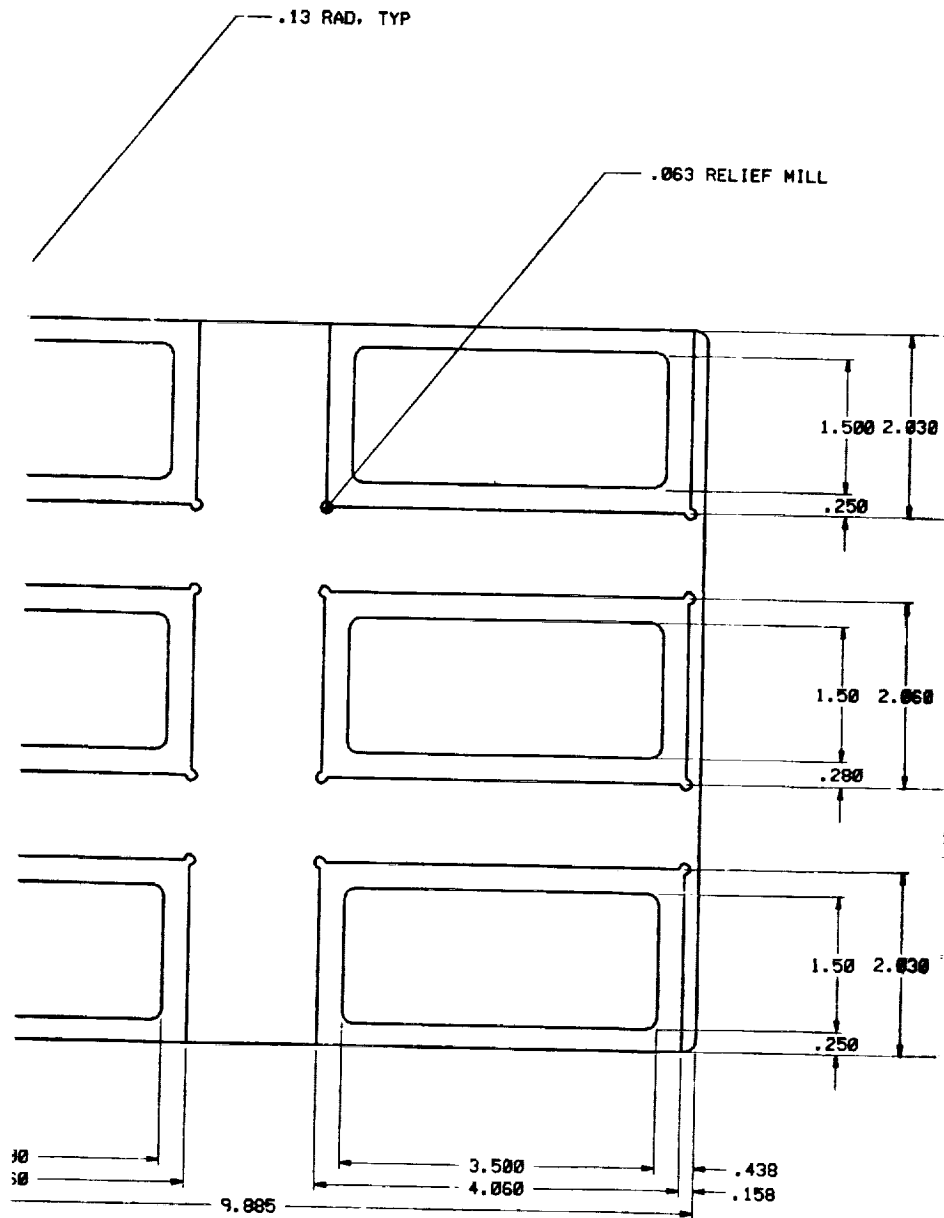
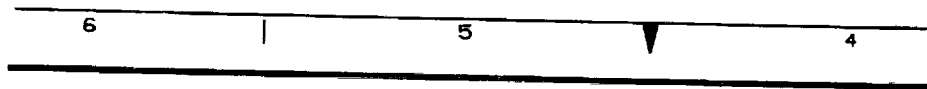
2 FOLDOUT FRAME

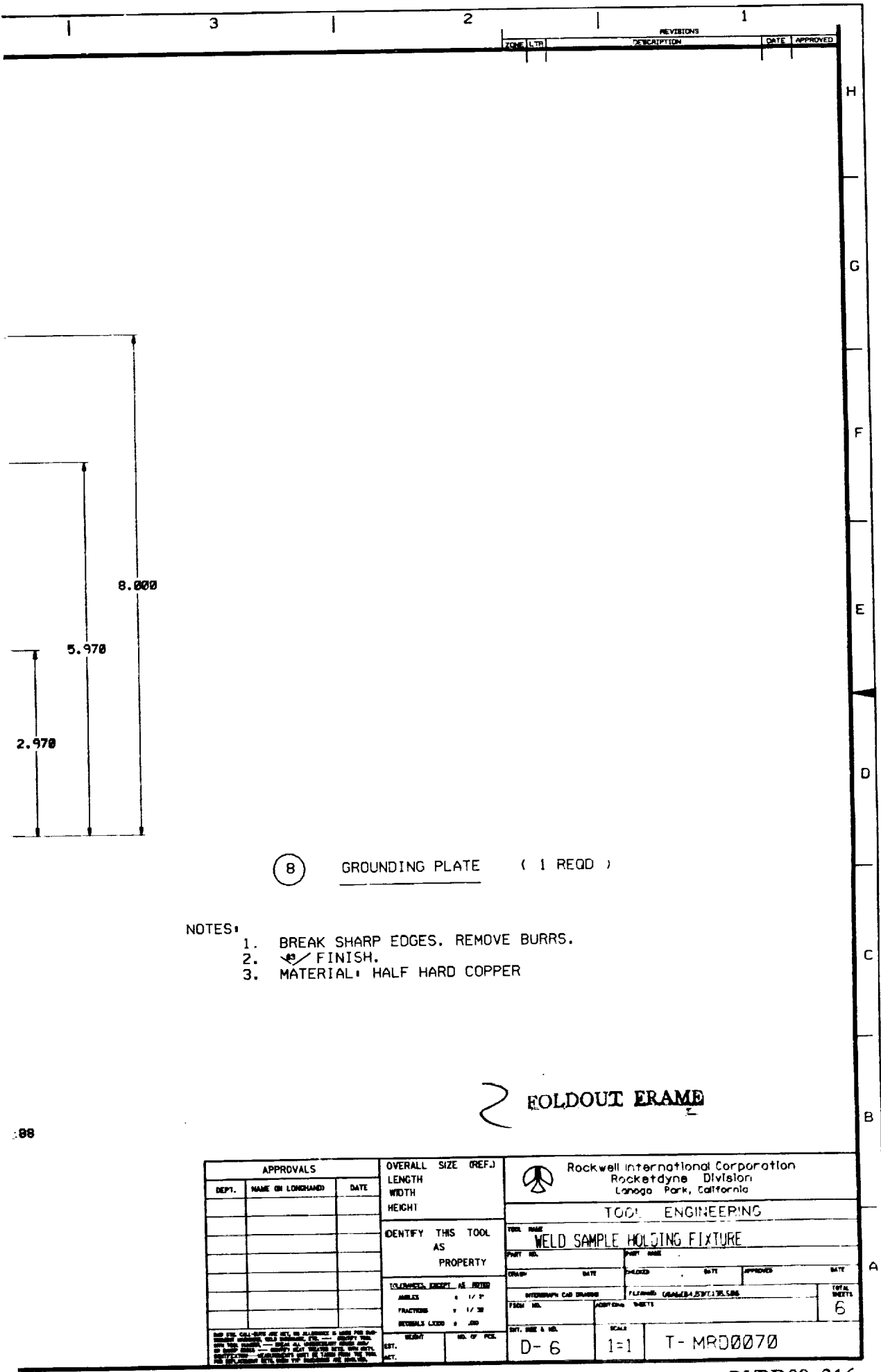
NOTES:

1. BREAK SHARP EDGES. REMOVE BURRS.
2. ☒ FINISH.
3. MATERIAL: 6061-T6 ALUMINUM

APPROVALS			OVERALL SIZE (REF.)		Rockwell International Corporation Rocketdyne Division Canoga Park, California	
DEPT.	NAME OR LONGHAND	DATE	LENGTH	WIDTH	TOOL ENGINEERING	
					TOOL NAME WELD SAMPLE HOLDING FIXTURE	
					PART NO. PART NAME	
					DATE CHECKED DATE APPROVED DATE	
					INFORMATION CAD DRAWING FILE NAME: 08A4264.5702175.M05	
					FROM NO. ADDITIONAL SHEETS	
					TOTAL SHEETS 6	
<small>NOTES: ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED. DIMENSIONS IN PARENTHESES ARE FOR INFORMATION ONLY. DIMENSIONS IN PARENTHESES ARE FOR INFORMATION ONLY. DIMENSIONS IN PARENTHESES ARE FOR INFORMATION ONLY.</small>			IDENTIFY THIS TOOL AS PROPERTY THICKNESS EXCEPT AS NOTED ANGLE ± 1/2° FRACTIONS ± 1/32 DECIMALS LESS ± .005		DWT. NO. & NO. D-5 1-1 T-MRC0070	







(B) GROUNDING PLATE (1 REQD)

- NOTES:
1. BREAK SHARP EDGES. REMOVE BURRS.
 2. \checkmark FINISH.
 3. MATERIAL: HALF HARD COPPER

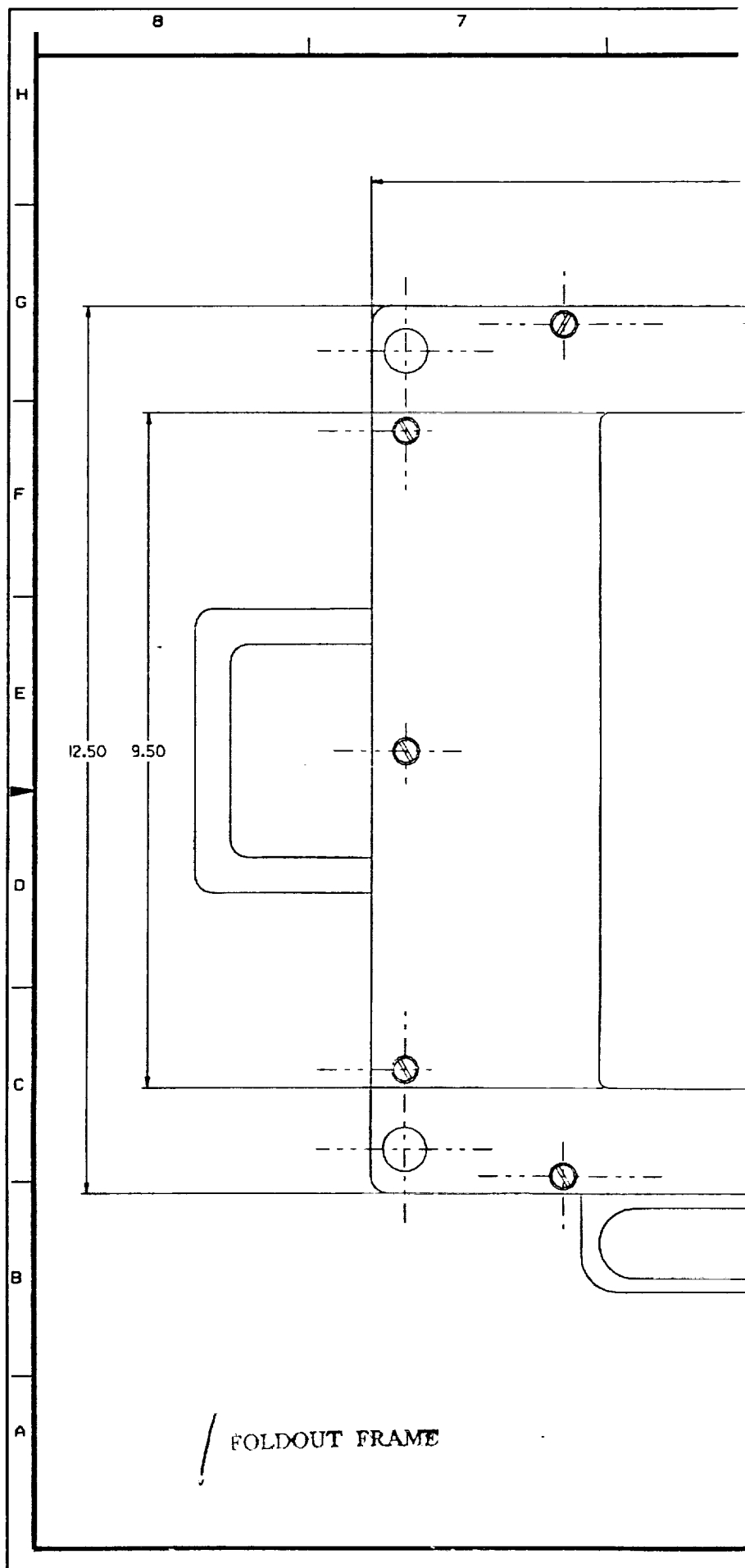
2 FOLDOUT FRAME

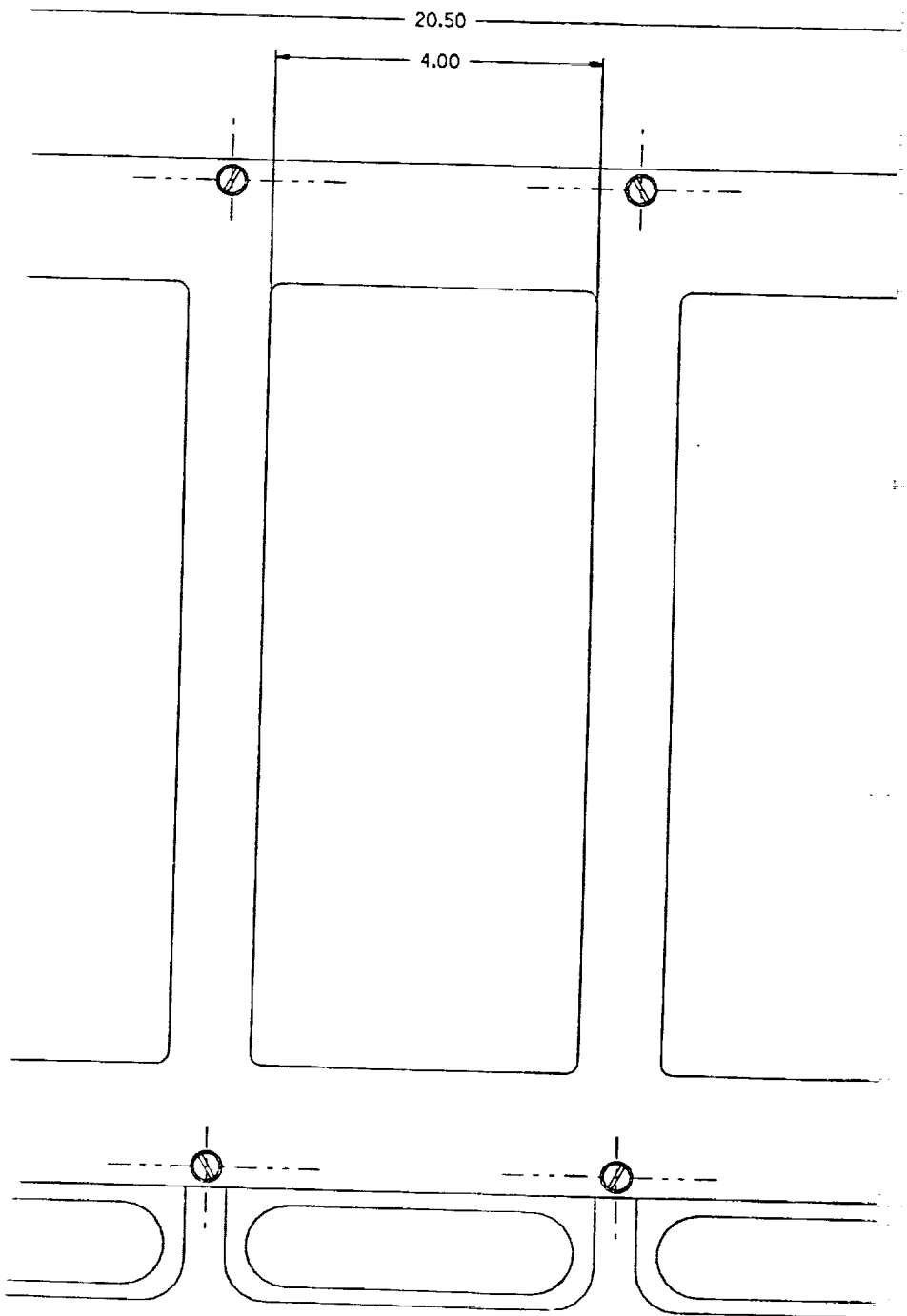
APPROVALS			OVERALL SIZE (REF.)		Rockwell International Corporation Rocketdyne Division Lanega Park, California	
DEPT.	NAME ON LONGHAND	DATE	LENGTH	WIDTH	TOOL ENGINEERING	
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					PART NO. DATE FILED DATE APPROVED DATE	
					IDENTIFY THIS TOOL AS PROPERTY	
					TOOLING NO. DATE FILED DATE APPROVED DATE	
					FRANCHISE 1/2 3/4	
					REWORKS USED 0 200	
					T- MRD0070	
					D- 6 1=1	
					T- MRD0070	

Appendix 4

RI/RD89-216

A4-1





RI/RI

A

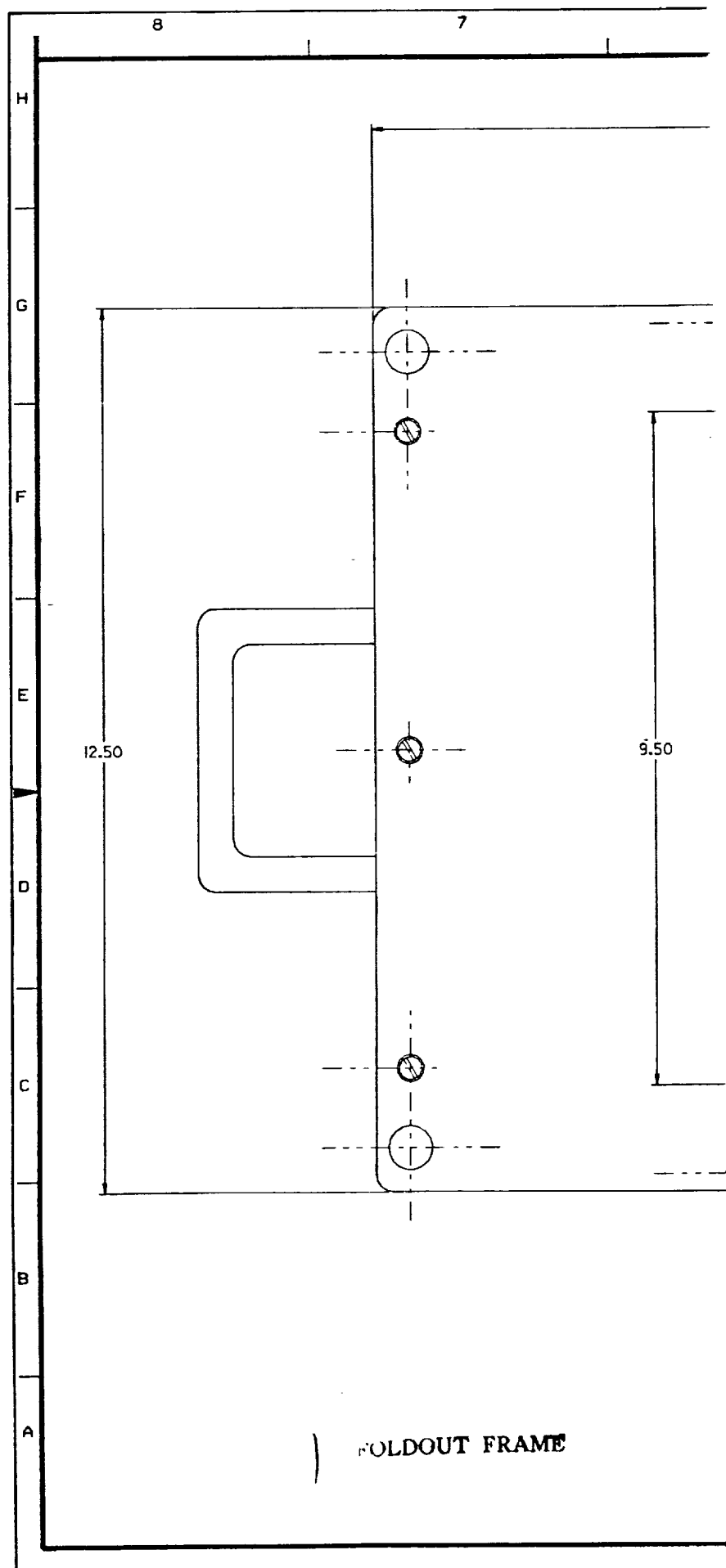
Frames: 1, 2, 3

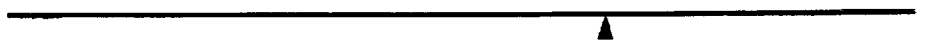
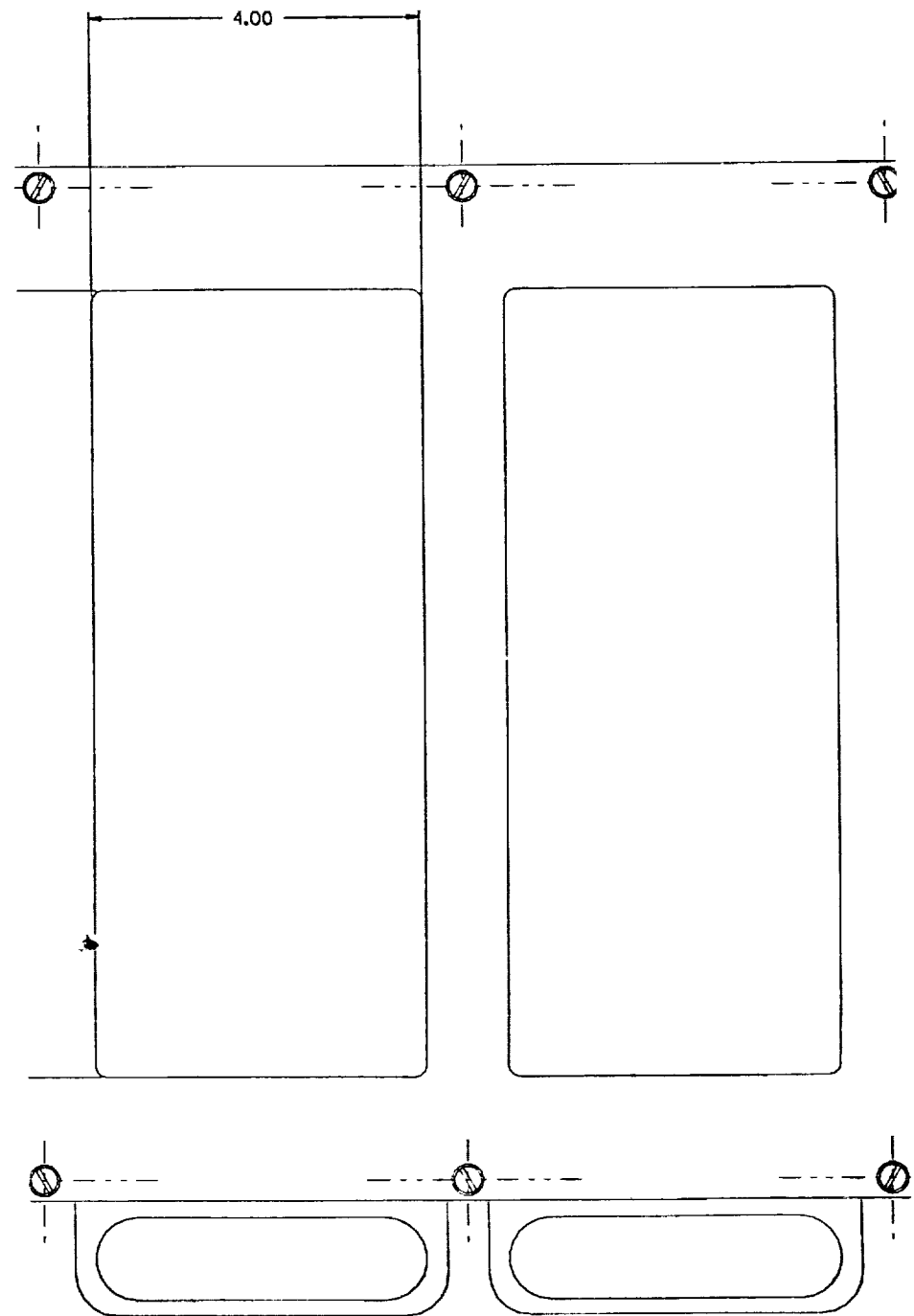
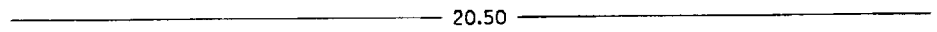
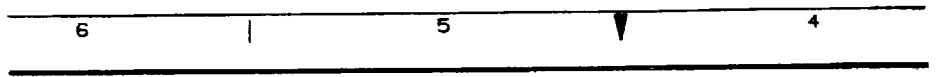
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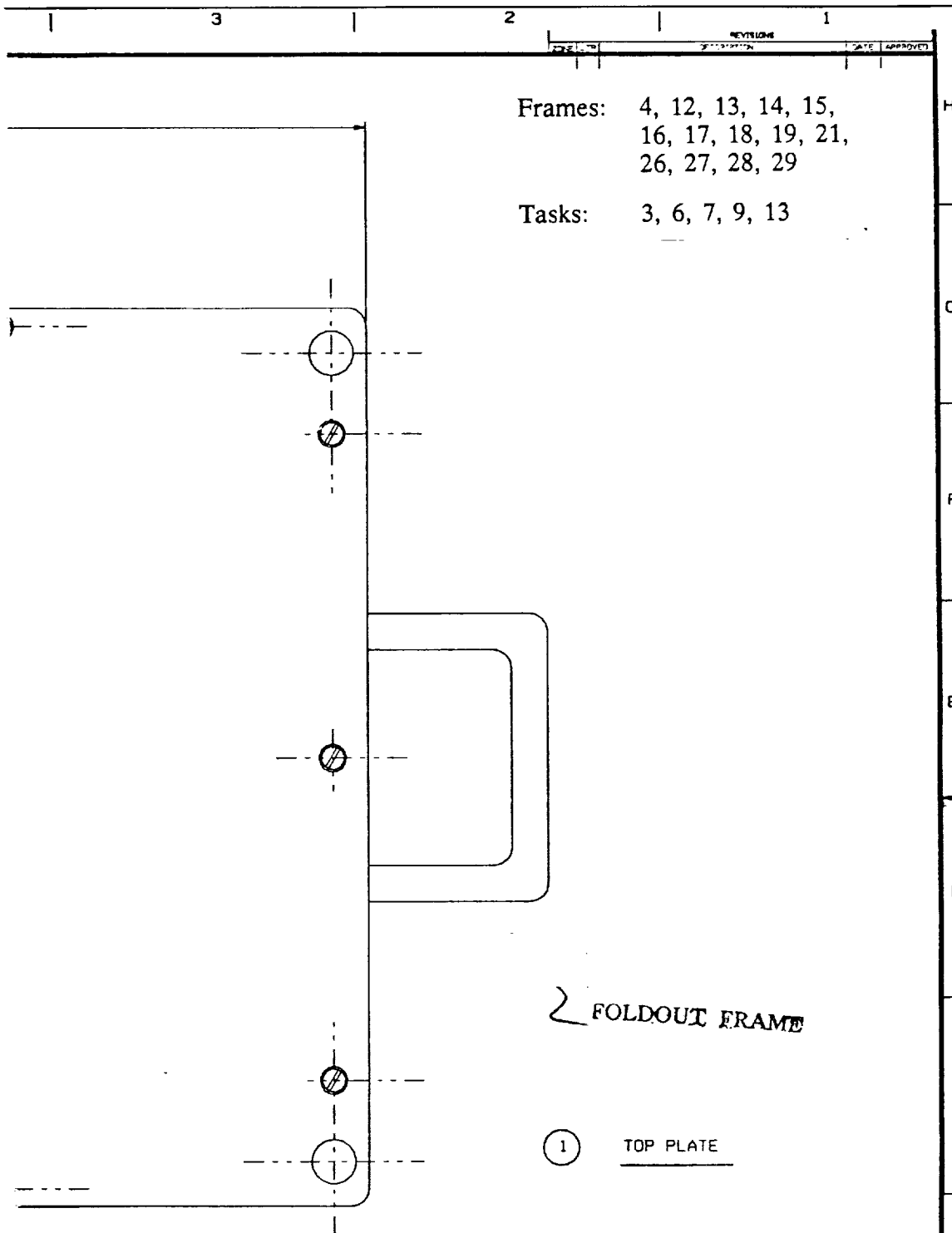
3			2			1																																																								
DATE			REVISIONS			DATE																																																								
TIME			DESCRIPTION			APPROVED																																																								
<p style="text-align: center; font-weight: bold;">2 FOLDOUT FRAME</p> <p style="text-align: center;">(1) TOP PLATE</p>																																																														
<p>NOTES:</p> <ol style="list-style-type: none"> BREAK SHARP EDGES. REMOVE BURRS. ✓ FINISH. MATERIAL: 6061-T6 ALUMINUM 																																																														
APPROVALS <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th>DEPT.</th> <th>NAME OR LONGHAND</th> <th>DATE</th> </tr> </thead> <tbody> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> </tbody> </table>			DEPT.	NAME OR LONGHAND	DATE																						<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td colspan="2" style="text-align: center;">OVERALL SIZE (REF.)</td> <td colspan="2" style="text-align: center;"> </td> <td colspan="2" style="text-align: center;"> Rockwell International Corporation Rocketdyne Division Canoga Park, California </td> </tr> <tr> <td colspan="2" style="text-align: center;"> LENGTH WIDTH HEIGHT </td> <td colspan="2" style="text-align: center;"> TOOL ENGINEERING </td> <td colspan="2" style="text-align: center;"> WELD SAMPLE HOLDING FIXTURE </td> </tr> <tr> <td colspan="2" style="text-align: center;"> IDENTIFY THIS TOOL AS PROPERTY </td> <td colspan="2" style="text-align: center;"> DRAWN DATE CHECKED DATE APPROVED DATE </td> <td colspan="2" style="text-align: center;"> DATE SCALE T-MRD0070 </td> </tr> <tr> <td colspan="2" style="text-align: center;"> TOLERANCES DECIMAL IN. NOTES HOLEX ± 1/16" FRACTIONS ± 1/32" DECIMALS LOCK ± .005 </td> <td colspan="2" style="text-align: center;"> INTERIM CAD DRAWING FINISHED TOLERANCES ± .005 </td> <td colspan="2" style="text-align: center;"> TOTAL SHEETS 6 </td> </tr> <tr> <td colspan="2" style="text-align: center;"> REVISIONS NO. OF PAGES D-2 </td> <td colspan="2" style="text-align: center;"> SCALE 1=1 </td> <td colspan="2" style="text-align: center;"> T-MRD0070 </td> </tr> </table>						OVERALL SIZE (REF.)				Rockwell International Corporation Rocketdyne Division Canoga Park, California		LENGTH WIDTH HEIGHT		TOOL ENGINEERING		WELD SAMPLE HOLDING FIXTURE		IDENTIFY THIS TOOL AS PROPERTY		DRAWN DATE CHECKED DATE APPROVED DATE		DATE SCALE T-MRD0070		TOLERANCES DECIMAL IN. NOTES HOLEX ± 1/16" FRACTIONS ± 1/32" DECIMALS LOCK ± .005		INTERIM CAD DRAWING FINISHED TOLERANCES ± .005		TOTAL SHEETS 6		REVISIONS NO. OF PAGES D-2		SCALE 1=1		T-MRD0070	
DEPT.	NAME OR LONGHAND	DATE																																																												
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REVISIONS NO. OF PAGES D-2		SCALE 1=1		T-MRD0070																																																										

089-216

4-2



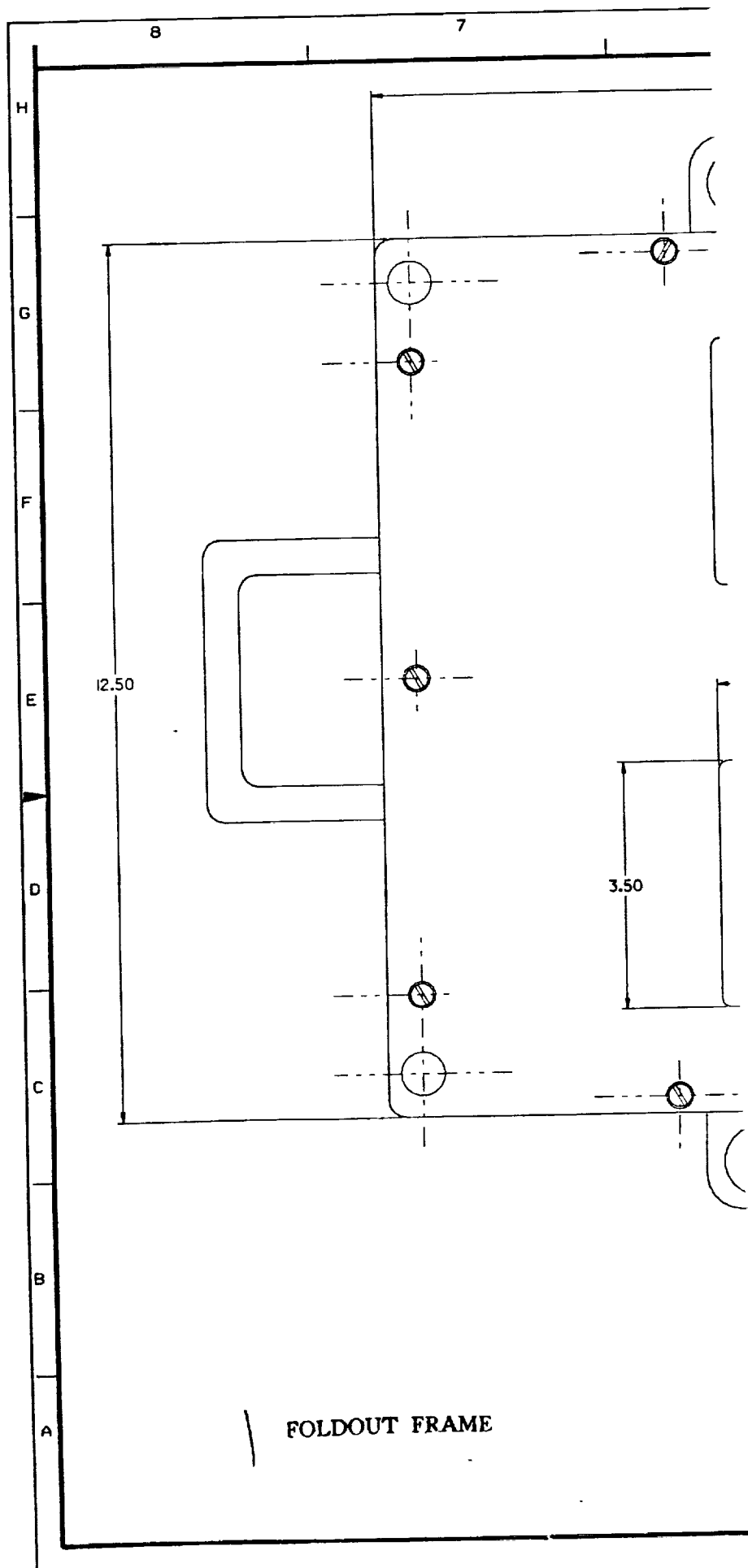


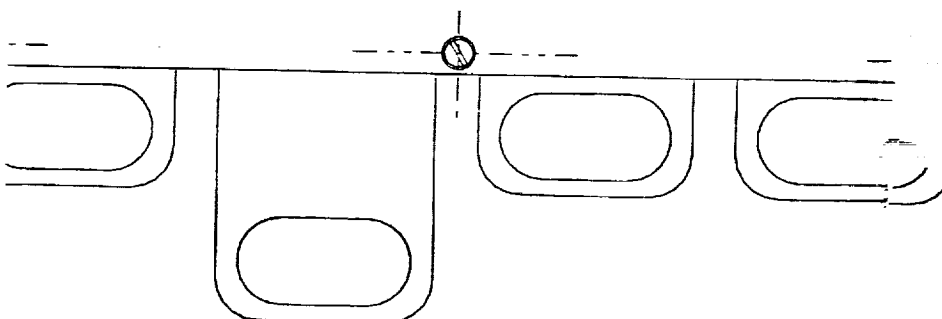
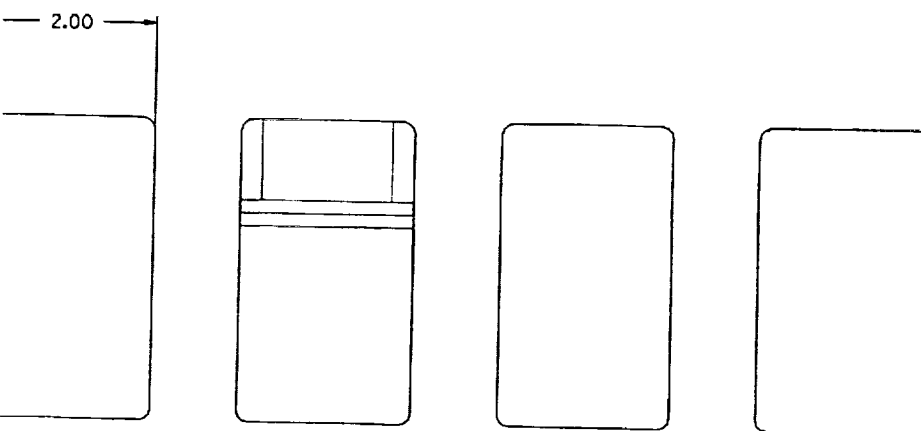
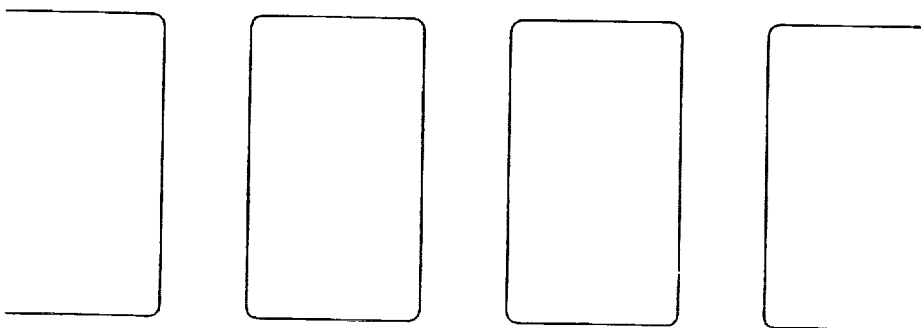
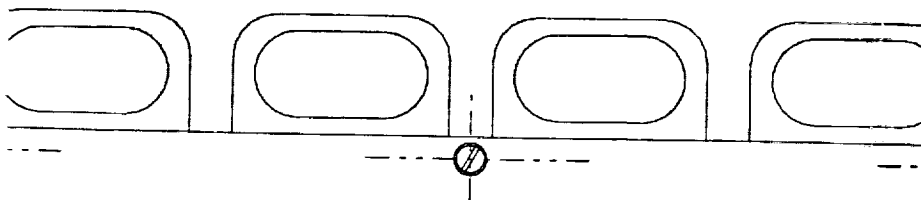
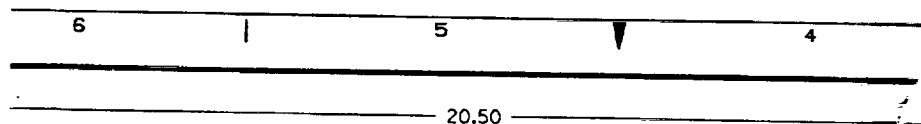


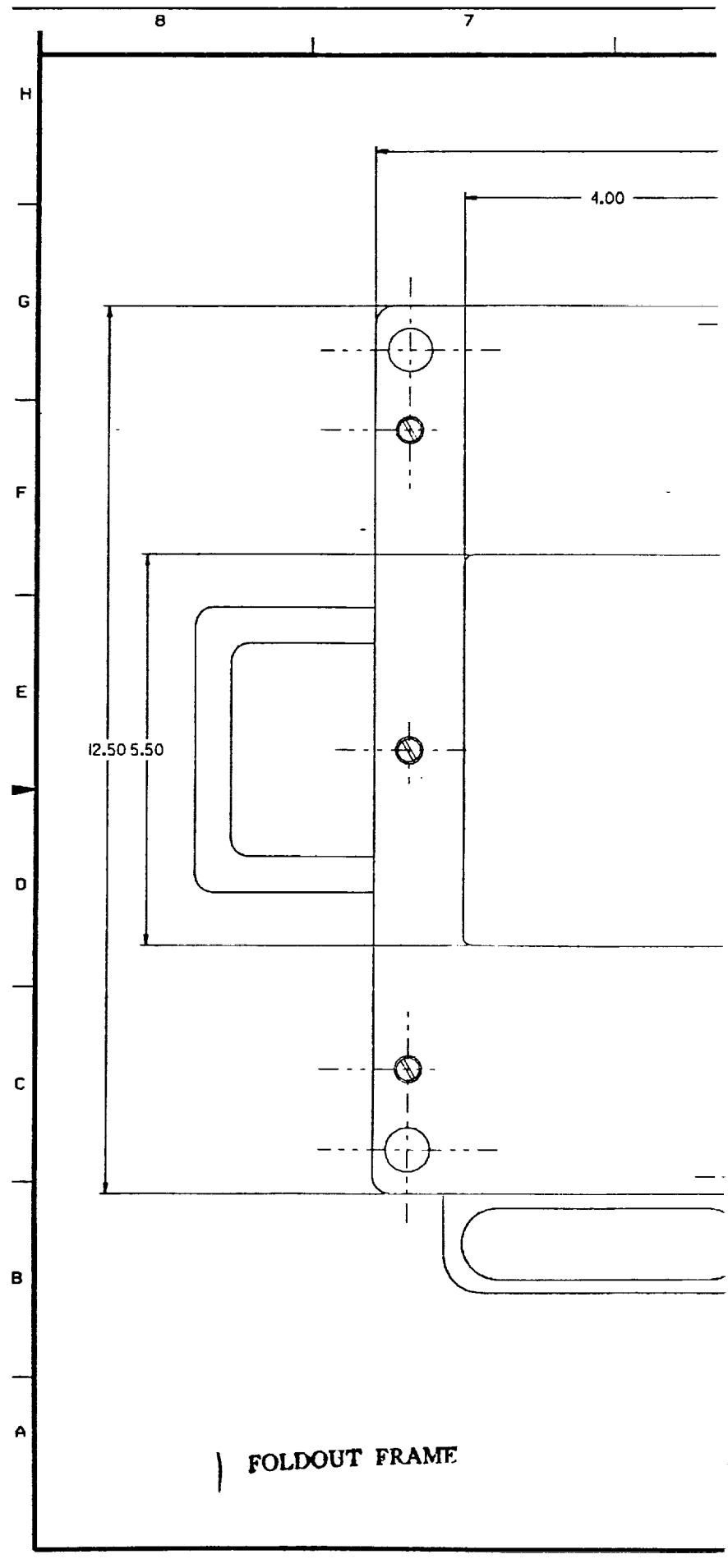
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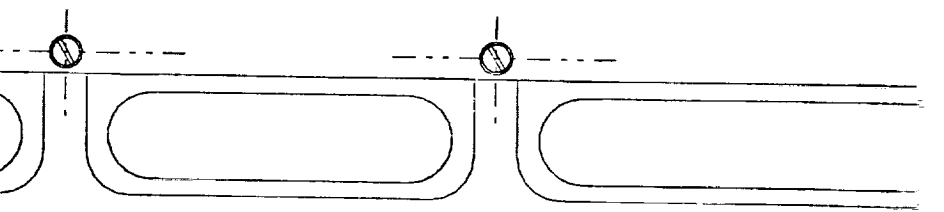
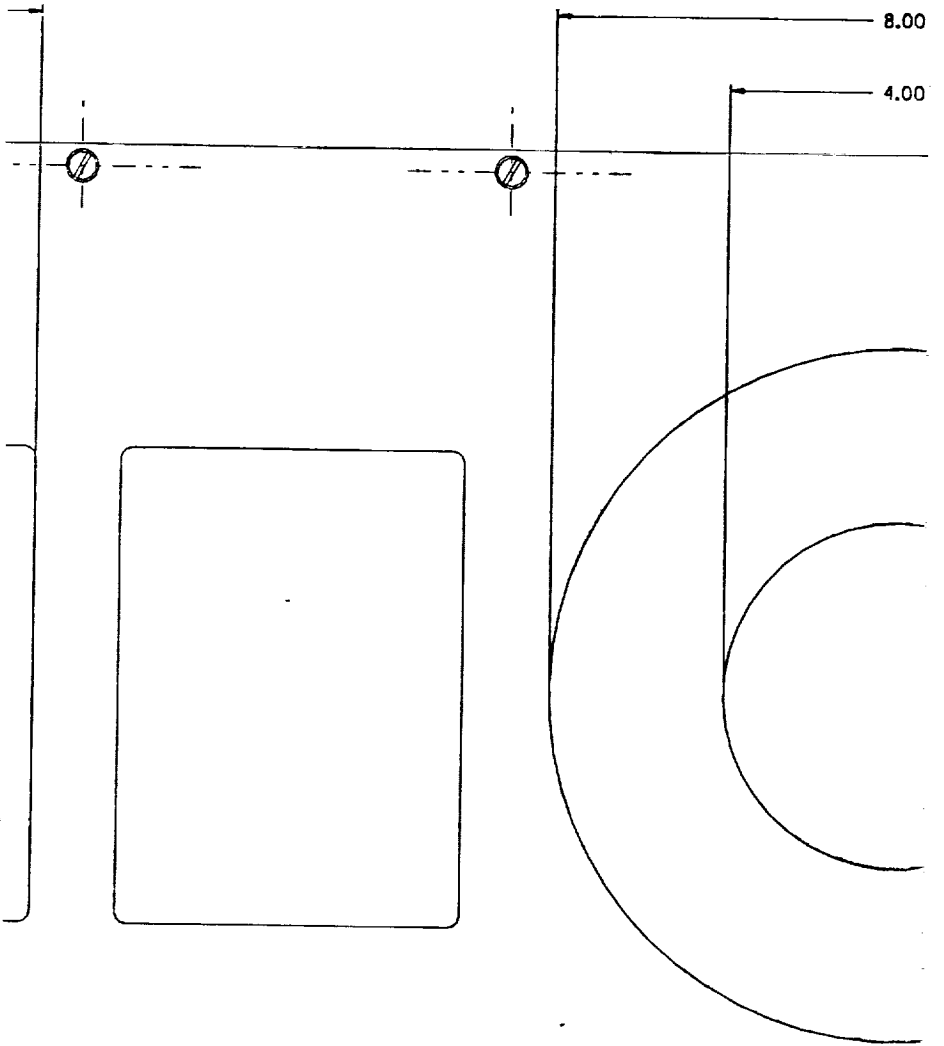
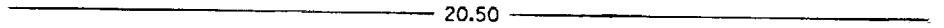
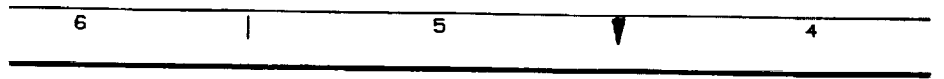
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2. ☒ FINISH.
3. MATERIAL: 6061-T6 ALUMINUM

APPROVALS			OVERALL SIZE (REF.)		Rockwell International Corporation Rocketdyne Division Canoga Park, California	
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					PART NO. PART NAME	
					DATE DESIGNED DATE APPROVED DATE	
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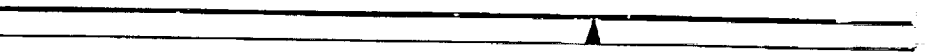








R/I



REVISIONS			DATE	APPROVED
NO.	DESCRIPTION	DATE	APPROVED	
1				

Frames: 8, 9, 10, 11
Task: 5

ORIGINAL PAGE IS
OF POOR QUALITY

FOLDOUT FRAME

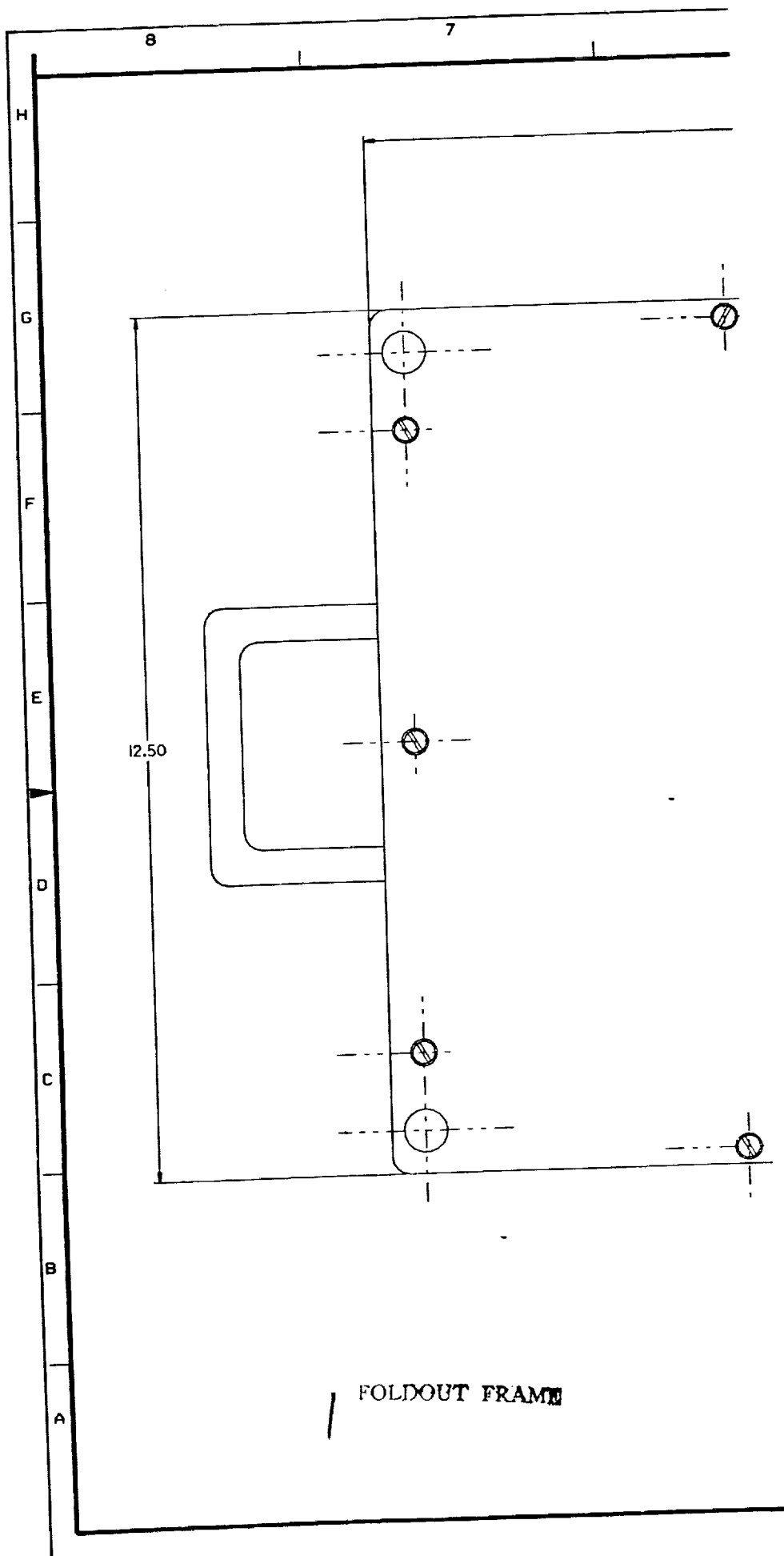
1 TOP PLATE

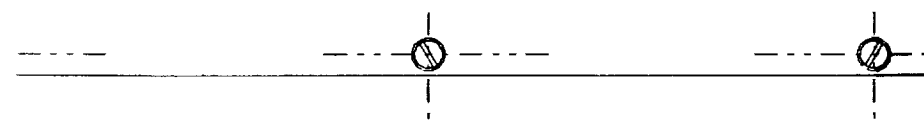
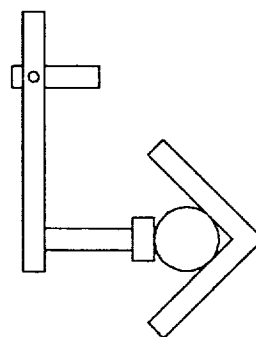
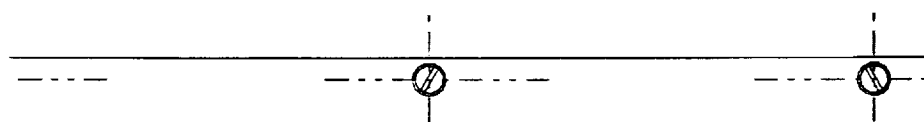
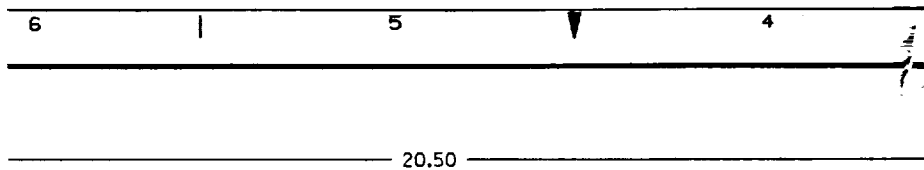
NOTES:
1. BREAK SHARP EDGES. REMOVE BURRS.
2. ☒ FINISH.
3. MATERIAL: 6061-T6 ALUMINUM

APPROVALS			OVERALL SIZE (REF.)	Rockwell International Corporation Rocketdyne Division Canoga Park, California	
DEPT.	NAME OR LONGHAND	DATE	LENGTH WIDTH HEIGHT	TOOL ENGINEERING	
			IDENTIFY THIS TOOL AS PROPERTY	TOOL NAME WELD SAMPLE HOLDING FIXTURE	
			TOLERANCES, UNLESS OTHERWISE SPECIFIED: FRACTIONS 1/16" DECIMALS .001" HOLE DIA. .0015"	DATE CHECKED DATE APPROVED DATE	
			EST. BY ACT.	TOTAL SHEETS 6	

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T-MPD0070





Appendix 5

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TIMELINE ESTIMATION

Accuracy of a timeline estimation for the EVA welding project requires a detailed script of all the individual procedural events. The simpler the events the more accurate are their time duration estimations. This analysis is based on the following assumptions and definitions, and on the experiment's simulation.

ASSUMPTIONS:

- No procedure delays due to malfunctions
- EVA translation rate of 0.5 ft/sec

DEFINITIONS:

- W = Welder
- CR = Controller / Retriever
- T = Activity duration
- T' = Nondriving concurrent activity duration
- T+ = Total time into EVA experiment

EVA ACTIVITY

DURATION (sec)

	T	T'	T+
BEGIN			
TASK 1.1			
Translate to tool crib (W & CR)	35		
Open tool crib (W & CR)	15		
Take and tether tools (W & CR)	60		
Close tool crib (W & CR)	10		
Translate to specimen booth-A (W & CR)	70		
Translate to welding booth (W)	25		
Open specimen booth-A (CR)		15	
Open welding booth (W)	15		
Remove specimen pack 1.2 from specimen booth (CR)		20	
Perform visual check of welding booth systems (W)	60		
Translate to welding booth (CR)		25	
Deploy camera system and activate (W)	30		
Fasten tray pack to welding booth door (CR)		15	
Verify operation of all systems (W & CR)	120		
Reset all systems to experiment start (W & CR)	15		
Deploy welding bench and amperage control (W)	30		485

EVA ACTIVITYDURATION (sec)

T T' T+

TASK 1.2**tray 1**

Install tray-1 and orient it (CR)	20		
Adjust camera (W)		5	
Retrieve torch and mount it on welder (W & CR)	30		
Verify torch controls (W & CR)	60		
Set welding computer parameters (CR)	5		600
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (4) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (5) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		690
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		785
Set welding computer parameters (CR)	5		
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		855

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		
Change trays (CR)	40		920
tray 2			
Install tray-2 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (4) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (5) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		1035
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		1130
Set welding computer parameters (CR)	5		
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		1195

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EVA ACTIVITYDURATION (sec)

	T	T'	T+
Position (3) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		
Change trays (CR)	40		1265
tray 3			
Install tray-3 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (4) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Position (5) torch over sample (W)	5		
Initiate - extinguish arc (W)	5		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		1380
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		1475
Set welding computer parameters (CR)	5		
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	10		
Position (2) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
			1535

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EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Check weldment (W & CR)	5		
Position (3) torch over sample (W)	5		
Initiate - mold - extinguish arc (W)	15		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		
Secure torch in rest fixture (W)	5		
Remove tray 3 and return to tray-pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-A (CR)	25		
Stretch (W)			
Return tray pack 1.2 (CR)	20		1645
TASK 1.3			
Remove tray pack 1.3 (CR)	20		
Translate to welding booth (CR)	25		
Fasten tray pack to welding booth door (CR)	15		1705
tray 4			
Install tray-4 and orient it (CR)	20		
Adjust camera (W)	5		
Retrieve and wear torch (W)	15		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		1820
Remove sample-B cover (CR)	5		
Retract guide (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		1895
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	145		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		
Change trays (CR)	40		2105

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A5-6

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
tray 5			
Install tray-5 and orient it (CR)	20		
Adjust camera (W)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		2200
Remove sample-B cover (CR)	5		
Retract guide (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		2275
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	145		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		
Change trays (CR)	40		2485
tray 6			
Install tray-6 and orient it (CR)	20		
Adjust camera (W)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		2580
Remove sample-B cover (CR)	5		
Retract guide (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		2655
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	145		2815

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		
Change trays (CR)	40		2865
tray 7			
Install tray-7 and orient it (CR)	20		
Adjust camera (W)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		2960
Remove sample-B cover (CR)	5		
Retract guide (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	45		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		3035
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	145		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		
Secure torch in rest fixture (W)	5		
Remove tray 7 and return to tray pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-A (CR)	25		
Stretch (W)			
Return tray pack 1.3 (CR)	20		3280
TASK 1.4			
Remove tray pack 1.4 (CR)	20		
Translate to welding booth (CR)	25		
Fasten tray pack to welding booth door (CR)	15		3340
tray 8			
Install tray-8 and orient it (CR)	20		
Adjust camera (W)	5		
Retrieve and wear torch (W)	15		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		3395

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EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		3485
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		3630
tray 9			
Install tray-9 and orient it (CR)	20		
Adjust camera (W)	5		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		3760
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		3905
tray 10			
Install tray-10 and orient it (CR)	20		
Adjust camera (W)	5		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		4035

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EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		4180
tray 11			
Install tray-11 and orient it (CR)	20		
Adjust camera (W)	5		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		4310
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Secure torch in rest fixture (W)	5		
Remove tray 11 and return to tray pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-A (CR)	25		
Stretch (W)			
Return tray pack 1.4 (CR)	20		4490
TASK 1.5			
Remove tube pack (CR)	20		
Translate to welding booth (CR)	25		
Fasten tube pack to welding booth door (CR)	15		4550
tray 12			
Install tray-12 and orient it (CR)	20		
Open tube case across door (CR)	15		
Install T-1 in jig (CR)	15		
Adjust camera (W)	5		
Retrieve and wear torch (W)	15		
Set welding computer parameters (CR)	5		
Position torch over sample (W)	5		4630

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	95		
Check weldment (W & CR)	10		
Remove weldment and return to case (CR)	15		4755
Reorient tray (CR)	15		
Install T-2 in jig (CR)	15		
Adjust camera (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	95		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		4915
Reorient tray (CR)	15		
Install T-3 in jig (CR)	15		
Adjust camera (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	95		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		5075
Reorient tray (CR)	15		
Install T-4A,B in jig (CR)	15		
Adjust camera (W)	5		
Set welding computer parameters (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	95		
Check weldment (W & CR)	10		
Remove weldment and return to case (CR)	15		5245
Reorient tray (CR)	15		
Install T-5A,B in jig (CR)	15		
Adjust camera (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	95		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		5405
Reorient tray (CR)	15		
Install T-6A,B in jig (CR)	15		
Adjust camera (W)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		5450

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EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Weld joint (W)	95		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		5565
TASK 1.6			
Secure torch in rest fixture (W)	5		
Retrieve welding head (W & CR)	30		
Reorient tray (CR)	15		
Adjust camera (W)	5		
Install T-7 in jig (CR)	15		
Position and clamp welding head around tube (W)	15		
Set welding computer parameters (CR)	5		
Activate motor calibration (CR)	60		
Activate welding sequence (W)	75		
Remove welding head (W)	10		
Check weldment (W & CR)	10		
Remove weldment and return to case (CR)	15		5825
Install T-8A in jig (CR)	15		
Position and clamp welding head around tube (W)	15		
Install and clamp T-8B in welding head (W)	15		
Activate welding sequence (W)	75		
Remove welding head (W)	10		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		5975
TASK 1.7			
Install T-9 in jig (CR)	15		
Position and clamp welding head around tube (W)	15		
Set welding computer parameters (CR)	5		
Activate welding sequence (W)	75		
Remove welding head (W)	10		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		6115
Install T-10 in jig (CR)	15		
Position and clamp welding head around tube (W)	15		
Set welding computer parameters (CR)	5		
Activate welding sequence (W)	75		
Remove welding head (W)	10		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		6255
Install T-11 in jig (CR)	15		
Position and clamp welding head around tube (W)	15		
Set welding computer parameters (CR)	5		
Activate welding sequence (W)	75		6365

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Remove welding head (W)	10		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		6395
Install T-12 in jig (CR)	15		
Position and clamp welding head around tube (W)	15		
Set welding computer parameters (CR)	5		
Activate welding sequence (W)	75		
Remove welding head (W)	10		
Check weldment (W & CR)	5		
Remove weldment and return to case (CR)	15		
Return welding head to storage (CR)	20		
Pack tube case (CR)	15		
Remove tray 12 and return to tube pack (CR)	10		
Remove tube pack from door (CR)	15		6595
Translate to specimen booth-A (CR)	25		
Translate to specimen booth-B (W)		25	
Return tube pack (CR)	20		
Open specimen booth-B (W)		15	
Secure and close specimen booth-A (CR)	30		
Remove tray pack 2.1 from booth-B (W)		20	
Translate back to welding booth (CR)	25		6695
Translate back to welding booth (W)		25	
CREWMEMBER ROLES ARE EXCHANGED			
W become CR and CR become W	30		6725
TASK 2.1			
Fasten tray pack 2.1 to welding booth door (CR)	15		6740
tray 13			
Install tray-13 and orient it (CR)	20		
Retrieve and wear manual torch (W)	15		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	10		
Cover sample-A (CR)	5		6885
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		6900

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		7025
tray 14			
Install tray-14 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		7150
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		7290
tray 15			
Install tray-15 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		7415
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		7555
tray 16			
Install tray-16 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		7595

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		7680
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Secure torch in rest fixture (W)	5		
Remove tray 16 and return to tray pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-B (CR)	25		
Stretch (W)			
Return tray pack 2.1 (CR)	20		7855
TASK 2.2			
Remove tray pack 2.2-3 (CR)	20		
Translate to welding booth (CR)	25		
Fasten tray pack to welding booth door (CR)	15		7915
tray 17			
Install tray-17 and orient it (CR)	20		
Retrieve and engage filler wire feeder (W & CR)	30		
Retrieve and wear torch (W)	15		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch and feeder over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment and evaluate (W & CR)	20		
Cover sample-A (CR)	5		8100
Set welding computer parameters (CR)	5		
Remove sample-B cover (CR)	5		
Position torch and feeder over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	75		
Check weldment and evaluate (W & CR)	30		
Cover sample-B (CR)	5		
Disengage and store feeder (W & CR)	30		
Change trays (CR)	40		8300

EVA ACTIVITY**DURATION (sec)**

T T' T+

TASK 2.3**tray 18**

Install tray-18 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		8380
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		8435
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		8490
Remove sample-D cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-D (CR)	5		8545
Remove sample-E cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-E (CR)	5		8600
Remove sample-F cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-F (CR)	5		8655

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EVA ACTIVITYDURATION (sec)

	T	T'	T+
Remove sample-G cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-G (CR)	5		8710
Remove sample-H cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-H (CR)	5		
Change trays (CR)	40		8805
tray 19			
Install tray-19 and orient it (CR)	20		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		8880
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		8935
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		8990
Remove sample-D cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-D (CR)	5		9045
Remove sample-E cover (CR)	5		
Position torch over sample (W)	5		9055

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EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-E (CR)	5		9100
Remove sample-F cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-F (CR)	5		9155
Remove sample-G cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-G (CR)	5		9210
Remove sample-H cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-H (CR)	5		
Change trays (CR)	40		9305
tray 20			
Install tray-20 and orient it (CR)	20		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		9380
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		9435
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		9480

EVA ACTIVITYDURATION (sec)

	T	T'	T+
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		9490
Remove sample-D cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-D (CR)	5		9545
Remove sample-E cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-E (CR)	5		9600
Remove sample-F cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-F (CR)	5		9655
Remove sample-G cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-G (CR)	5		9710
Remove sample-H cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-H (CR)	5		
Secure torch in rest fixture (W)	5		
Remove tray 20 and return to tray pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-B (CR)	25		
Stretch (W)			
Return tray pack 2.2-3 (CR)	20		
Remove tray pack 2.3 (CR)	20		
Translate to welding booth (CR)	25		
Fasten tray pack to welding booth door (CR)	15		9900

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
tray 21			
Install tray-21 and orient it (CR)	20		
Retrieve and wear torch (W)	15		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		9990
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		10045
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		10100
Remove sample-D cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-D (CR)	5		10155
Remove sample-E cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-E (CR)	5		10210
Remove sample-F cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-F (CR)	5		10265

EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Remove sample-G cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-G (CR)	5		10320
Remove sample-H cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-H (CR)	5		
Change trays (CR)	40		10415
tray 22			
Install tray-22 and orient it (CR)	20		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		10490
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		10545
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		10600
Remove sample-D cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-D (CR)	5		10655

EVA ACTIVITYDURATION (sec)

	T	T'	T+
Remove sample-E cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-E (CR)	5		10710
Remove sample-F cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-F (CR)	5		10765
Remove sample-G cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-G (CR)	5		10820
Remove sample-H cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-H (CR)	5		
Change trays (CR)	40		10915
tray 23			
Install tray-23 and orient it (CR)	20		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		10990
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		11045

EVA ACTIVITYDURATION (sec)

	T	T'	T+
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		11100
Remove sample-D cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-D (CR)	5		11155
Remove sample-E cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-E (CR)	5		11210
Remove sample-F cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-F (CR)	5		11265
Remove sample-G cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-G (CR)	5		11320
Remove sample-H cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-H (CR)	5		
Secure torch in rest fixture (W)	5		
Remove tray 23 and return to tray pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-B (CR)	25		
Stretch (W)			
Return tray pack 2.3 (CR)	20		11450

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EVA ACTIVITY**DURATION (sec)****T T' T+****TASK 2.4**

Remove tray pack 2.4 (CR)	20		
Translate to welding booth (CR)	25		
Fasten tray pack to welding booth door (CR)	15		11510

tray 24

Install tray-24 and orient it (CR)	20		
Retrieve and wear manual torch (W)	15		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	300		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		11875

Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	300		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		12240

tray 25

Install tray-25 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	150		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		12440

Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	150		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		12655

tray 26

Install tray-26 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		12690

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EVA ACTIVITY**DURATION (sec)**

	T	T'	T+
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	100		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		12805
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	100		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Change trays (CR)	40		12970
tray 27			
Install tray-27 and orient it (CR)	20		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	60		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		13080
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	60		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		
Secure torch in rest fixture (W)	5		
Remove tray 27 and return to tray pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-B (CR)	25		
Stretch (W)			
Return tray pack 2.4 (CR)	20		13240
TASK 2.5			
Remove tray pack 2.5 (CR)	20		
Translate to welding booth (CR)	25		
Fasten tray pack to welding booth door (CR)	15		13300
tray 28			
Install tray-28 and orient it (CR)	20		
Retrieve and wear torch (W)	15		
Set welding computer parameters (CR)	5		
Remove sample-A cover (CR)	5		
Position torch over sample (W)	5		13350

EVA ACTIVITYDURATION (sec)

	T	T'	T+
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-A (CR)	5		13395
Remove sample-B cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-B (CR)	5		13450
Remove sample-C cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-C (CR)	5		13505
Remove sample-D cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-D (CR)	5		13560
Remove sample-E cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-E (CR)	5		13615
Remove sample-F cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-F (CR)	5		13670
Remove sample-G cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-G (CR)	5		13725

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EVA ACTIVITYDURATION (sec)

	T	T'	T+
Remove sample-H cover (CR)	5		
Position torch over sample (W)	5		
Initiate arc and establish weld pool (W)	5		
Weld joint (W)	30		
Check weldment (W & CR)	5		
Cover sample-H (CR)	5		13780
Shut-down welding system (CR)	5		
Store and secure torch (W & CR)	30		
Remove tray 28 and return to tray pack (CR)	10		
Remove tray pack from door (CR)	15		
Translate to specimen booth-B (CR)	25		
Stretch (W)		10	
Return tray pack 2.5 (CR)	20		
Retract and store all welding booth systems (W)		30	
Secure and close specimen booth-B (CR)	30		
Shut-down all support systems except for cooling (W)	10		
Translate to welding booth (CR)	25		
Secure and close welding booth (W)		30	
Translate to tool crib (W & CR)	95		
Open tool crib (W & CR)	15		
Return tools and debris if any (W & CR)	60		
Secure and close tool crib (W & CR)	20		
Translate to hatch (W & CR)	35		14175

END

EVA WELDING EXPERIMENT DURATION:

= 14175 SECONDS
= 236.25 MINUTES
= **3.94 HOURS**



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16. Abstract This report summarizes the results of a 12-month study to define a space-based experiment for development of welding-in-space capability. Welding techniques for use in a space environment were evaluated. Gas tungsten arc welding using a hollow electrode was selected as the leading candidate for a proposed Space Shuttle experiment. No safety or technology items were found which would impede an astronaut in conducting a manual welding experiment in the bay of the Space Shuttle.					
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